

BULLETIN
of the
**American Association of
Petroleum Geologists**

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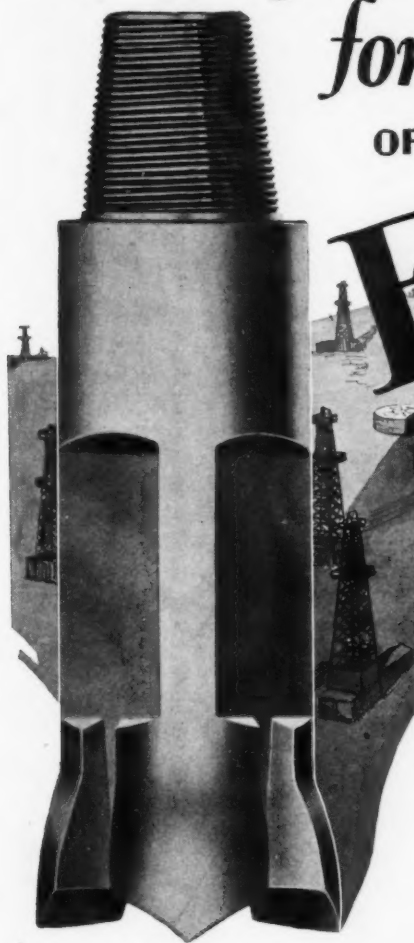




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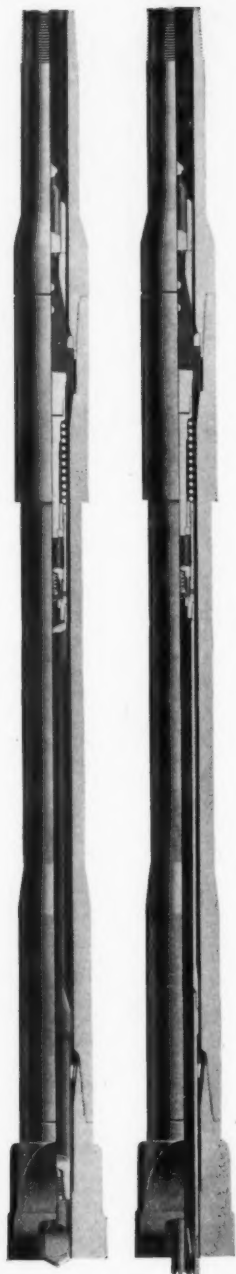
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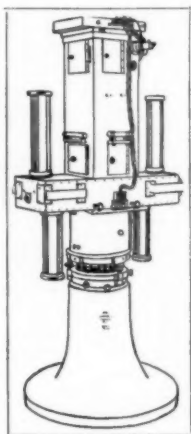
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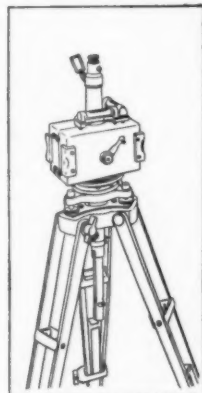
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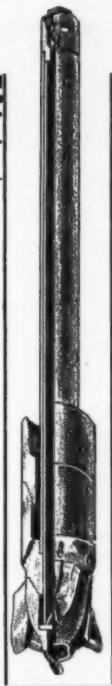
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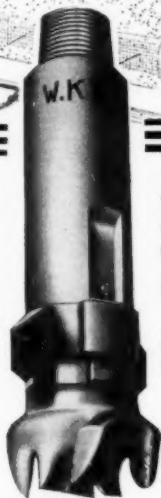
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The Bulletin of the American Association of Petroleum Geologists is published by the Association on or about the 15th of each month. Editorial and publication office, 504 Tulsa Building, Tulsa, Oklahoma, Post Office Box 1852.

The subscription price to non-members of the Association is \$15.00 per year (separate numbers \$1.50) prepaid to addresses in the United States. For addresses outside the United States, an additional charge of \$0.40 is made on each subscription to cover extra wrapping and handling.

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TULSA, OKLAHOMA

Entered as second-class matter at the Post Office of Tulsa, Okla., under the Act of March 3, 1879. Acceptance for mailing at special rate of postage provided for in section 1103, Act of October 3, 1917, authorized March 9, 1923.

MID-WEST PRINTING CO., TULSA, OKLA., U. S. A.

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BULLETIN

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Hale Mountain Section in North- west Arkansas

By ALBERT W. GILES and
EUGENE B. BREWSTER

Causative Agents of Sulphate Re- duction in Oil Well Waters

By ROY L. GINTER

Additional Data on Sulphate-Reduc- ing Bacteria in Soils and Waters of Illinois Oil Fields

By EDSON S. BASTIN and
FRANK E. GREER

Permian Structure and Stratigra- phy of Northwestern Oklahoma and Adjacent Areas

By R. L. CLIFTON

Magnetometer Study of the Caddo- Shreveport Uplift, Louisiana

By WILLIAM M. BARRET

BULLETIN
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**AMERICAN ASSOCIATION OF
PETROLEUM GEOLOGISTS**

JANUARY 1930

**DENSITY, POROSITY, AND COMPACTION OF
SEDIMENTARY ROCKS¹**

L. F. ATHY²
Ponca City, Oklahoma

ABSTRACT

An efficient laboratory method of obtaining the bulk volume of a chunk sample of rock is explained. The relation between depth of burial and the density, porosity, and compaction of different types of sediment is discussed and data are presented. These relations can be expressed by exponential equations. Compaction as a cause of structure is substantiated by computation and data. A table is given showing the relation in north-central Oklahoma between depth of burial, height of buried hills, and closure resulting from compaction. An approximate idea of the depth of material eroded from a given area may be obtained by density or porosity studies.

INTRODUCTION

That compressibility of sediments has been an important factor in developing structure has been pointed out by many geologists, but very little has been done to establish by positive evidence its relative importance. The theory of differential compacting of sediments, the settling of sediment over buried hills, and the effect these phenomena have on the structure of the formations involved has been discussed by Monnett,³

¹Manuscript received by the editor, September 7, 1929.
Published by permission of the Continental Oil Company.

²Geologist and geophysicist, Continental Oil Company.

³V. E. Monnett, "Possible Origin of Some of the Structures of the Mid-Continent Oil Field," *Econ. Geol.*, Vol. 17 (1922), pp. 194-200.

Blackwelder,¹ Teas,² Rubey,³ and others. None of these have supplied quantitative data on the relative importance of compaction, or the relation of compaction to depth of burial, or pressure either from the weight of overburden or from disturbances in the earth's crust. Few quantitative data on the relationship of depth of burial to porosity, density, and compaction, in deeply buried rock specimens such as might be obtained from well cuttings, mines, or tunnels, had been published previous to the excellent work by Hedberg.⁴ In spite of the limited number of samples available to Hedberg, his findings were similar, in general, to those found by the writer and his associates in a study of many hundred samples from northern Oklahoma made during the summer and fall of 1926. In this paper the writer wishes to furnish further evidence concerning the density, porosity, and compaction of buried sedimentary rocks and their importance in the development of structure.

LABORATORY METHOD FOR DETERMINING BULK DENSITY AND POROSITY OF SEDIMENTARY ROCKS

There are many methods by which the absolute density, bulk density, and porosity of materials may be measured. These methods vary much in degree of accuracy and speed of execution. Perhaps the most accurate is that used by Melcher in his work on the porosity of oil sands.⁵ He coats the sample by dipping it in paraffine, and then obtains the bulk volume by the loss of weight in water method. The paraffine is then burned off and a correction made for the volume of the paraffine. Another excellent method is employed by Westman in ceramic work.⁶ He determines the bulk volume and density of briquettes by weighing them in mercury in an especially constructed mercury balance. The accuracy of several of the various methods is suitable for most purposes,

¹E. Blackwelder, "The Origin of Central Kansas Oil Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 4 (1920), pp. 89-94.

²L. P. Teas, "Differential Compacting, the Cause of Certain Claiborne Dips," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 7 (1923), pp. 370-77.

³W. W. Rubey, "Progress Report on a Subsurface Study of the Pershing Oil and Gas Field, Osage County, Oklahoma," *U. S. Geol. Survey Bull.* 751 (1923-24), Pt. II, pp. 51-54.

⁴H. D. Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 1035-73.

⁵A. F. Melcher, "Determination of Pore Space of Oil and Gas Sands," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 65 (1921), pp. 469-77; also "Texture of Oil Sands with Relation to the Production of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8 (1924), pp. 758-59.

⁶A. E. R. Westman, "The Mercury Balance—An Apparatus for Measuring the Bulk Volume of Brick," *Jour. Amer. Chem. Soc.* (May, 1926), p. 311.

but the length of time required to make a determination is a serious objection.

The method developed by the writer consists of weighing the sample in mercury with a Jolly balance, a sufficient mass being suspended to submerge the sample. An illustration of the apparatus is shown in Figure 1. Before making any observations, zero reading is established on the Jolly balance by adjusting the level of the mercury so that the pin point is exactly above the mercury surface. A known mass (M) is next added which is sufficient to submerge the largest sample to be tested. The specimen of rock is inserted under the prongs in the mercury, the spring is run out to the equilibrium point, and the mercury level adjusted until the pin point is again exactly above the mercury surface. The force necessary to lift the mass M in air and the sample in mercury can now be determined from the reading on the Jolly balance. For accurate work, the temperature of the mercury must be recorded, and the elastic constant of the spring must be frequently determined.

By this method, the volume or bulk density of a chunk sample may be quickly determined because the dry sample requires no preparation or treating, and two weighings and one temperature reading complete the observations. The dry sample is weighed in air on a chainomatic balance, then weighed on the Jolly balance in mercury of known temperature and density.

The bulk volume and bulk density are easily calculated from the following equations.

$$\text{Bulk volume} = \frac{(W + M) - \frac{w}{k}}{D}$$

$$\text{Bulk density} = \frac{W D}{(W + M) - \frac{w}{k}}$$

Where W is the weight of sample in air

M is the weight of suspended mass M

w is the reading on the Jolly balance with the sample in mercury and M suspended

k is the elastic constant of the spring

D is the density of mercury at the observed temperature

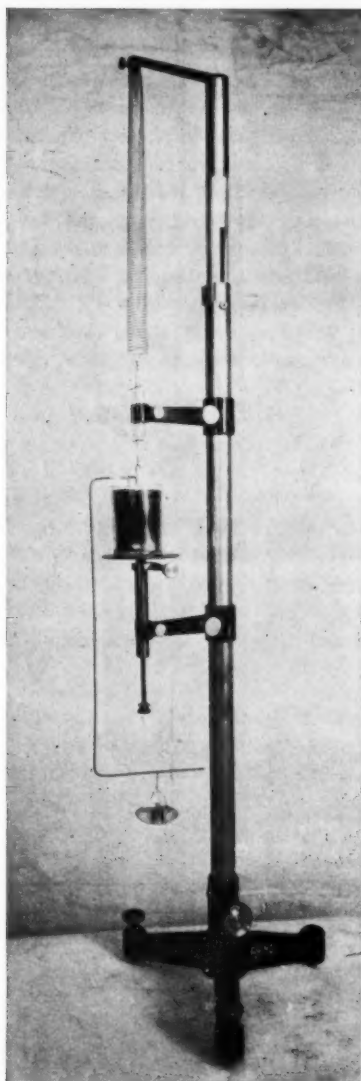


FIG. 1.—Apparatus for determining bulk volume of rock samples.

The accuracy of the method is shown by a comparison of volumes of samples determined by weighing them in mercury and volumes determined by Melcher's paraffine method.

TABLE I
COMPARISON OF VOLUMES DETERMINED BY THE JOLLY BALANCE-MERCURY METHOD
AND MELCHER'S PARAFFINE METHOD

Number Sand Sample	Volume by Jolly Balance-Mercury Method (Cubic Centimeters)	Volume by Melcher's Paraffine Method (Cubic Centimeters)	Difference in Percentage
1	3.832	3.827	.130
2	3.833	3.829	.104
3	3.197	3.192	.156
4	4.011	4.006	.124
5	3.881	3.875	.155
6	3.767	3.762	.133
7	3.747	3.745	.053
8	3.784	3.779	.132
9	4.320	4.314	.130
10	3.707	3.700	.188

The volumes obtained by the Jolly balance-mercury method average about 0.15 per cent higher than they do by Melcher's method. The correct volume is probably between the two. The value obtained by weighing in mercury may be too large, because mercury, by virtue of its negative capillarity, will tend to arch over the pores on the surface of the sand. The volume by the paraffine method may be slightly too small because some of the paraffine may be absorbed by the sand, thereby causing too large a volume of paraffine to be deducted from the volume of the coated sample.

The greatest advantage of the Jolly balance-mercury method is in the speed with which the observations may be made. The weighing on the Jolly balance is slightly faster than the weighing on the chainomatic. Weighings and calculations can be made on at least ten samples per hour.

The density of the mercury is not appreciably altered by impurities from the samples, because such matter floats on the surface and may readily be skimmed off. After running twenty or thirty samples, the mercury may be changed or cleansed of the impurities and used again.

The method employed to determine absolute density is the well-known pycnometer method. Pycnometers and evacuating tubes prepared by Melcher¹ for obtaining the absolute density of oil sands are

¹A. F. Melcher, *op. cit.*

used. They are constructed so that the air may be evacuated from the dry sample in the pycnometer and the distilled water at the same time. After evacuation is complete, the water is allowed to fill the pycnometer. An electrically driven vacuum pump is used to remove the air from the water and sample. Correct volume and density relations are obtained by holding the pycnometer in a constant temperature bath for 30 minutes. At least two determinations were made on each sample in order to check the results.

The porosity is calculated by use of the following formula.

$$1 - \frac{\text{Bulk density}}{\text{Absolute density}} \times 100 = \text{per cent porosity}$$

FACTORS CAUSING DENSITY AND POROSITY VARIATIONS

Density, as used in this work, refers to the bulk density or rock density of the specimen. Absolute density is the mineral density. Absolute density, bulk density, and porosity are so related that any one of them may be calculated if the other two are known.

The porosity of a sediment at the time of its deposition depends on the size, shape, degree of uniformity of size and shape, and the mode of packing of the individual grains. In very fine material the porosity may be very high and the bulk density very low because the surface area is enormous and the adsorption of liquid and gas is great. Also in very fine sediments, such as clays, the grains are ordinarily very irregular in shape and, as a result, the bulk density is low. In sand, the porosity is independent of the coarseness, provided the grains are of one size and spherical. In general, the sands of highest porosity are coarse and even-textured, and the grains are of irregular shape.

After a sediment has been deposited, buried, and indurated, several additional factors determine its porosity; chief among these are closer spacing of grains, deformation and granulation of grains, recrystallization, secondary growth and cementation, and, in some sediments, solution. The density of the rock is influenced by the same factors, but any factor tending to reduce pore space also increases the bulk density. Closer spacing of grains is caused primarily by pressure, either lateral or vertical, and is brought about by expulsion of interstitial and adsorbed water, by rearrangement of grains, or by the breaking or granulation of grains.

Deformation of grain is caused primarily by pressure changes and is especially noticeable in shales and sandy shales. Chloritic and mica-

ceous particles bend around more rigid sand grains, tiny lath-shaped grains are broken into pieces, angular edges are broken off, et cetera. Even with coarse sand grains, probably a small amount of granulation and regelation takes place at the points of contact. As the grains are under enormous pressures for geologic ages, deformation of the individual particle must be very considerable.

Secondary growth and cementation by deposition from solutions in circulating waters are of prime importance in causing rock induration and reduction of pore space. It is noteworthy that these are the only governing factors which may be independent of pressure and, incidentally, of depth of burial.

RELATION BETWEEN COMPACTION AND PRESSURE AS SHOWN BY DENSITY AND POROSITY CHANGES

The continued application of pressure, either lateral or vertical, has one definite tendency,—reduction in volume, or compaction. The compaction is brought about through closer spacing of grains, recrystallization, and, in some sediments, decomposition. In other words, there is a reduction of porosity and an increase in density. However, the amount of compaction is not exactly proportional either to reduction of pore space or to increase of density; recrystallization may take place in which heavy minerals such as mica are developed, and as a result the compaction would be represented by an increase in the density of the minerals. A change in mineral density of a sediment may change either the porosity or bulk density or both.

As we do not know the original volume of sediments of different ages, we can not measure the amount of compaction directly. Compaction must be computed from measured changes in porosity, bulk density, and absolute density. If we use porosity determinations as the basis of our calculations, we must assume that all reduction of pore space is caused by compaction. The assumption is slightly in error, however, because the reduction of pore space may have been due partly to cementation. With shales the latter objection will not hold, and probably 95 per cent of a decrease in porosity or increase in density is expressed by compaction.

DENSITY AND POROSITY OF UNCONSOLIDATED SURFACE SEDIMENTS

The writer has made no attempt to measure the porosity and density of freshly deposited sediments. There is considerable literature on the subject, however. Shaw¹ found that the water content of different recent

¹E. W. Shaw, "The Role and Fate of Connate Water in Oil and Gas Sands," *Amer. Inst. Min. Met. Eng. Bull.* 103 (1915), p. 1451.

mud deposits on the sea coast ranged from 40 per cent to 90 per cent. Meinzer¹ says that Mississippi delta mud has a porosity ranging from 80 to 90 per cent. Lee² found porosities of surface alluvium to be as follows: coarse sand, 39-41 per cent; medium sand, 41-48; fine sand, 44-49; and fine sandy loam, 50-54 per cent. Hedberg³ found that Pleistocene loess from Collinsville, Illinois, had a bulk density of 1.438 and a porosity of 47 per cent, and recent Missouri River alluvium, a bulk density of 1.538 and a porosity of 42.68 per cent. Residual sediments formed by the weathering of shales in the vicinity of Ponca City, Oklahoma, vary in density from 1.39 to 1.72 when dry and 1.52 to 1.85 when still moist. Porosities of the dry samples vary from 37 to 48 per cent.

Average bulk densities of the top 100 feet of most surface clays are assumed to be between 1.30 and 1.60, and the porosities between 40 and 50 per cent. Although surface clays may vary in porosity from 50 to 90 per cent, it is probable that an average porosity of about 50 per cent is obtained after a few tens of feet of burial.

COMPACTION OF SANDSTONE

The relation between density or porosity and the amount of compaction a sand has undergone is not definite. Sands are too variable in character, especially in the amount of cementing material which has entered them. Even non-calcareous sands vary in the amount of fine sediment they contain as well as in the amount of siliceous cement. As a result we find sands of very different porosities and densities at different depths. Many sands at 4,000 feet are more porous and less dense than very similar sands at shallow depths. In other words, changes caused by pressure in sands are small in comparison with changes caused by other agencies. This statement is substantiated by laboratory tests. A column of St. Peter sand deposited under water settles about 11 per cent with continuous jarring under atmospheric pressure. If placed under 4,000 pounds pressure, the compaction is about 2 per cent more, or 13 per cent in all. Therefore, most of the compaction in this sand is due to rearrangement of the grains and occurs soon after deposition.

Observed densities of sands range from 1.60 to 2.50 and porosities from 6 to 40 per cent. Sands of even greater porosity are known. The

¹O. E. Meinzer, "The Occurrence of Ground Water in the United States," *U. S. Geol. Survey Water Supply Paper 489* (1923), p. 8.

²C. H. Lee and A. J. Ellis, *U. S. Geol. Survey Water Supply Paper 446* (1919), pp. 121-23.

³H. D. Hedberg, *op. cit.*, p. 1042.

density of most sand samples measured by the writer ranges from 1.85 to 2.40 and the porosity from 9 to 30 per cent.

COMPACTION OF LIMESTONES

Density of dominantly calcareous sediments is also extremely variable. Solution is an important factor in causing the variability. Another factor is the crystallinity. In general, crystalline limestones have a much greater density than the amorphous types. Chalk is exceedingly porous, as a rule. Alteration of aragonite to calcite or calcite to dolomite causes volume and density changes which can not be readily evaluated.

Among several hundred samples of limestone tested in the laboratory were chalks with a density as low as 2.1 and crystalline limestones as dense as 2.7. The density of most limestone ranges from 2.5 to 2.6. Chalks may have a porosity as high as 25 per cent and crystalline limestone may have a porosity of less than 1 per cent.

Among the crystalline limestones there is a noticeable increase in density with depth, but no quantitative relationship has been established.

COMPACTION IN MIXED SEDIMENTS

Calcareous shales, calcareous sands, sandy limestones, shaly limestones, and sandy shales vary in bulk density and porosity almost as much as nearly pure limestones, shales, and sands. Calcareous shales are intermediate in density between limestone and shale, shaly sands between sand and shale, et cetera. Slightly sandy shales are similar to pure shales in density, but calcareous shales are much denser and less porous than pure shales because of the greater density of calcium carbonate and the presence of more cementing material. Compaction of calcareous or sandy shales is comparable with that of pure shales.

COMPACTION OF SHALES

Within any specified locality relatively pure shales have about the same density and porosity at a specified depth of burial. Density and porosity of non-calcareous, non-organic shales, containing not enough pyrite or other heavy minerals to be noticed readily, differ with depth of burial or the amount of pressure they have suffered. In such shales, either density or porosity is a measure of the compaction the shale has undergone, because relatively little cementation occurs in shales and nearly all changes in density or porosity are a direct result of increased pressures. Among all the different sediments, in shale alone is compaction resulting from pressure of large magnitude. As already stated, surface

clays have a density of about 1.50 and a porosity of 40-50 per cent. Permian shales now near the surface in the Thomas field in northern Oklahoma have densities whose average is about 2.15 and shales from the lower part of the Pennsylvanian nearly 4,000 feet below the surface have a density of more than 2.55. Porosities are found to range from less than 4 per cent to nearly 20 per cent in shales ranging from lower Pennsylvanian to upper Permian in age. Density-depth and porosity-depth relations have been established and will be reported later.

Wet clay was put under pressure in a hydraulic press in an effort to determine approximately the relation between pressure and compaction. Unlike sand, the clay was readily compressed, but the maximum amount of compaction which might be caused by a specified pressure could not be measured because of the time factor. The amounts of compaction of clay samples under different pressures and for various intervals of time are given in Table II. The clay was submerged in water during compression to prevent evaporation of the absorbed water.

TABLE II
COMPACTION OF WET CLAY (PER CENT OF ORIGINAL VOLUME)

<i>Pressure per Square Inch</i>	<i>Time</i>						
	<i>1 Hour</i>	<i>3 Hours</i>	<i>7 Hours</i>	<i>15 Hours</i>	<i>24 Hours</i>	<i>1 Week</i>	<i>5 Weeks</i>
<i>Tons</i>							
$\frac{1}{2}$	26.8	27.0	....	29.4	29.9	....	....
1	26.8	29.9	30.7	32.1	33.0	....	....
2	33.1	33.9	34.2	35.3	....	37.7	39.6
4	....	....	....	35.7	36.4	....	....
8	....	36.9	....	39.3	....	....	....

The original porosity of the clay was approximately 50 per cent.

DENSITY-DEPTH RELATIONS IN SEDIMENTS

A general statement and theoretical discussion of the relation of the depth of burial to the density of sediment is included in the preceding paragraphs. Definite relations have actually been observed from a laboratory study of more than 2,200 samples taken from wells in north-eastern Oklahoma and parts of Texas.

In relatively pure shales, a definite relation exists between density and pressure or depth of burial. Whether or not the pressures developing these higher densities came entirely from the weight of the overburden is not yet determined, as all samples studied were taken from areas of

structural deformation and some of the compaction may have resulted from vertical or lateral pressures in the earth's crust. In any case, the density should increase with depth, but over an upward moving center the densities may be higher than in undisturbed strata. Lateral pressures may have some effect on the densities of sediments, but in general such pressures would not alter the density-depth relations to such an extent that the differences could be noticed within short distances.

In Figure 2, densities of samples from wells in the Mervine, South Ponca, Thomas, Garber, and Blackwell fields are plotted. The sediments range from the Enid Red-beds of Permian age to the Cherokee shales in the base of the Pennsylvanian, a stratigraphic range of about 4,000 feet. These samples came from a relatively small area within which approximately the same amounts of sediments were deposited after Cherokee time with no intervening unconformity. Consequently, it is safe to assume that all parts of a given stratigraphic horizon within the area were under approximately the same overburden. Hence, in the accompanying figure, densities were plotted against stratigraphic depth below the surface beds at the M. C. Garber Well No. 1, northeast of Garber, Oklahoma.

As shown in the figure, the densities are not constant for a given depth of burial, but vary through an appreciable range. The solid part of the curve represents the average density-depth relations for all the shale samples measured in the laboratory.

The broken part of the curve is an extension of the observed depth-density curve to include shales buried to shallower depths than those in northeastern Oklahoma, and is the hypothetical extension of the curve to the 1.4 ordinate, 1.4 being taken as the average density of surface clay.

The curve is expressed by the following equation.

$$D = B + A(1 - e^{-bx}), \text{ where}$$

D is the density to be calculated

B is 1.4 the density of surface clay

A is 1.3 the maximum density increase possible

b is a constant

x is the depth of burial

It is assumed, therefore, that density-depth relations in northern Oklahoma are closely represented by the logarithmic curve (Fig. 2) and by the preceding equation.

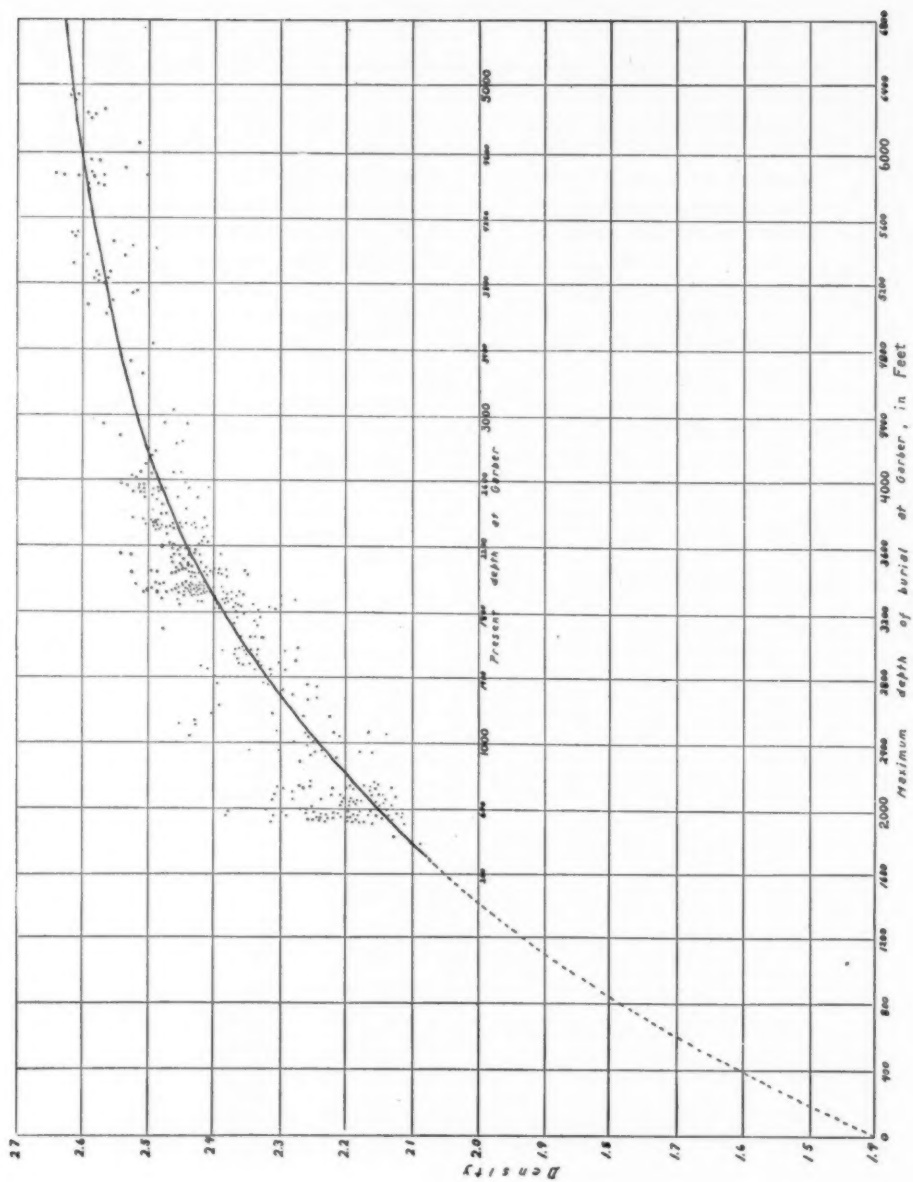


FIG. 2.—Density-depth curve.

Only the unbroken part of the curve has been determined by actual measurement. The remainder of the curve is hypothetical and should be tested by the measurement of densities of samples from areas where there has been little erosion since the sediments have been deposited.

POROSITY-DEPTH RELATIONS IN SEDIMENTS

The porosity of approximately 200 selected samples from cores taken in the area between Ponca City and Garber was determined in an effort to establish the relation between porosity and depth of burial and to ascertain whether porosity gives more definite data than bulk density on the compaction and depth of burial. The curve in Figure 3 was constructed from the average porosities measured at different stratigraphic depths. The unbroken part of the curve has been determined by actual

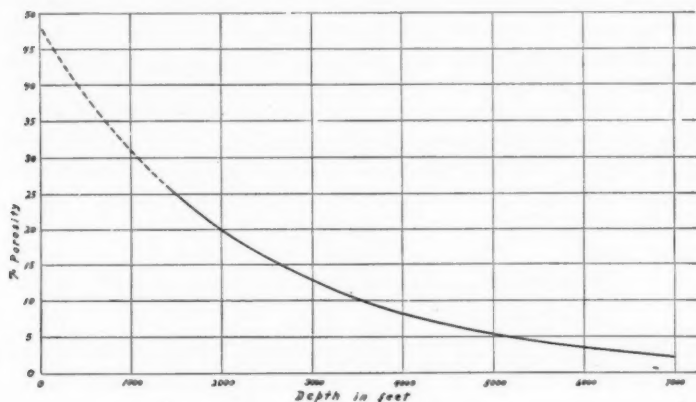


FIG. 3.—Porosity-depth curve.

measurement; the dashed part is hypothetical and represents the continuation of the known part to meet the ordinate representing the porosity of average surface clays. The hypothetical part represents the porosity-depth relation in the younger beds which have been removed in the area studied.

The porosity-depth relations are similar to the density-depth relations, and in fact can be calculated accurately from the density-depth curve in Figure 2. These relations can be expressed by a logarithmic equation of the form

$$P = p(e^{-bx}) \text{ where}$$

P is the porosity, p is the average porosity of surface clays, b is a constant, and x is the depth of burial.

Among the samples studied, the porosities of shale are as variable as the bulk densities at a given depth. It is evident from the rather extended study made that porosities are no more reliable than bulk densities in establishing the relation between compaction of sediments and their depth of burial. Most of the work on compaction carried on by the writer has been based on observed bulk densities rather than porosities, because the density determinations can be made much more easily and quickly. The work on porosity was carried far enough, however, to satisfy the writer that the results would be the same irrespective of whether density or porosity data were used.

A comparison of the relation of porosity of shale to overburden as found by Hedberg¹ in western Kansas with similar relations given in this paper for north-central Oklahoma shows a considerable divergence. For depths not exceeding 2,000 feet the porosities agree very well, but at greater depths the porosity does not decrease as rapidly in western Kansas as in north-central Oklahoma. Porosity-depth relations may follow a well-defined law, but evidently the relation varies from place to place. W. W. Rubey² has attempted to write an equation expressing this relation in terms of depth of burial and void ratio.

He finds from a study of Hedberg's data that

$$(D + B) \frac{P}{100 - P} = C, \text{ where}$$

D is the observed depth of burial, B is the eroded depth computed from a derived equation, P is the observed porosity, and C is a constant which varies in different areas. Porosities calculated by use of this equation agree very well with observed porosities in the Ranson, Phillips, and Lynn wells cited by Hedberg, but only the first of these can be seriously considered because insufficient data were available from the last two wells. An attempt to apply Rubey's equation to the porosity data from north-central Oklahoma met with no success.

It is the writer's opinion that had Hedberg more samples at his disposal he would not have found the porosity-depth relations as consistent as his data indicated. Porosity-depth relations for the few sam-

¹*Op. cit.*, p. 1058.

²W. W. Rubey, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11 (1927), pp. 621-32.

ples he used may be quite unlike the average of many samples, as is shown by the spread of points in Figure 2.

RELATIVE AMOUNT OF COMPACTION IN SEDIMENTS AT VARYING DEPTH

It is generally recognized that sandstones, limestones, and metamorphic and igneous rocks are practically incompressible. Most of the compaction that occurs in sands and limestones certainly takes place before cementation has progressed far. Compaction in clays and silts is very considerable and continues as long as the pressure on them increases. The relation between the amount of compaction a shale has suffered and the depth to which it has been buried can be calculated from either the density-depth curves or the porosity-depth curves given on previous pages. The amount of compaction a given shale sample has undergone can be calculated, if its porosity or bulk density is known, from the increase in bulk density or decrease in porosity since the time it was deposited, the initial density of clay under a few feet of overburden being taken as 1.4 and the porosity as 48 per cent.

The curve in Figure 4 represents compaction-depth relations in shale from northern Oklahoma. These relations may be expressed by the following logarithmic equation.

$$C = 1 - \frac{B}{B + A(1 - e^{-bx})}$$

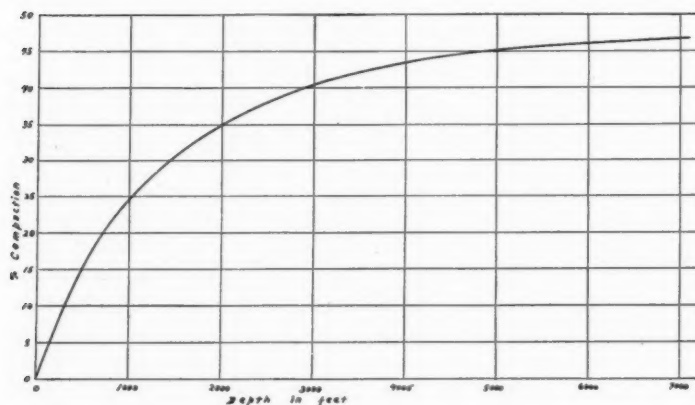


FIG. 4.—Compaction-depth curve.

where C is the compaction expressed as percentage of the original volume; B is 1.4, the average density of surface clay; A is 1.3, the average maximum density increase possible; b is a constant, and x is the total maximum depth of burial.

Near the Thomas pool, Oklahoma, Permian shales near the surface have a density of about 2.15 and a porosity of approximately 20 per cent, and have suffered a compaction of 35 per cent since deposition. The overburden which once covered the surface beds was 2,000 feet. Shales once buried 4,000 feet, and now at a depth of 2,000 feet at Thomas, have been compacted 43 per cent. At a total depth of burial of 6,000 feet, 4,000 feet deep at Thomas, compaction amounts to 46 per cent, and the volume is reduced to 54 per cent of the original.

Obviously, most of the compaction did not occur during the first few hundred feet of burial, as many geologists have thought. Only about 53 per cent of the total compaction possible at a depth of 6,000 feet had occurred when the depth of burial was 1,000 feet.

If the shales are saturated with water at all stages of burial, the compaction gives an idea of the amount of fluid forced out as burial proceeds. This information is of vital importance in making a study of the migration of oil from source beds, and indicates that compaction is perhaps the most important cause. It must be borne in mind that these curves for density, porosity, and compaction are tentative and may not apply in all areas. Only a part of the curve was actually obtained from experimental data, and that part is known to be representative of the relations as they exist only in northern Oklahoma.

COMPACTION AND CLOSURE OVER BURIED HILLS

Work on the density and porosity of sediments shows that compaction increases with depth. Should sediments of a homogeneous character be deposited over a horizontal plane surface, the only effect of gravitational compaction would be an increase in density, a decrease in porosity, and a decrease in thickness with depth. Should such a surface be covered with beds of unlike sediments, but each bed homogeneous in a lateral direction, the effects of gravitational compaction would be similar to those in the first situation except quantitatively. In either situation, the attitude of the beds would remain the same and no structure would develop. Should the beds vary laterally in character, then the amount of compaction would vary and structure would develop. Should an otherwise homogeneous shale contain large lenses

of sand or vary considerably in organic content, the compaction would vary accordingly and structure would develop in the overlying beds. On the contrary, should the sediments have been deposited on an uneven erosion surface, such as a granite or limestone hill, then structure would have developed as a result of compaction irrespective of the homogeneity of the sediments.

Let us assume that sediments are being deposited over a granite ridge which stands 500 feet above an otherwise plane surface. Sedimentation continues until 500 feet of shale have been laid down. At this time, nearly horizontal shale beds surround and just cover the crest of the granite ridge. Let us assume that a bed of sandstone is now deposited above the shale to serve as a marker upon which to obtain the structural data. This sandstone bed is supported by 500 feet of shale except at the ridge, where it rests on firm granite. As sedimentation continues and the overburden becomes greater, the 500 feet of shale is compressed, possibly to 450 feet, thereby lowering the level of the sandstone bed 50 feet in all places except where it lies on the granite hill. Obviously, 50 feet of closure has been developed in the sandstone bed. Closure is simultaneously being developed in the beds above the shale, but the amount of closure is progressively less in the upper beds. That this is true becomes evident when we consider that any of the upper beds are nearly horizontal when deposited and would remain so if no more sediments were put over them. When more sediments are added, the compression of the lower 500 feet of shale continues and the attitude of all beds, except the bed at the surface, is altered. Closure is developed in the beds above the granite ridge irrespective of whether they are limestone, sandstone, or shale. The sediments surrounding the granite hill must be largely shale or other sediments which compact appreciably.

The total amount of settling for a given thickness of sediment under a given load, and the amount of closure developed in beds over a buried hill of known height and depth relations, can be computed. Or if the closures on younger beds are known, as well as the approximate depth to the buried hill, then the height of the hill and the closure on other beds can be estimated.

L. J. Peters, of the Mellon Institute at Pittsburgh, worked out the following solution based on the equation for density-depth relations. In Figure 5, *NO* is the structure profile of a buried bed; *LM* is the position of the bed *NO* when it was deposited; *PQ* is a buried erosion surface on non-compressible strata; and *HK* is the surface of deposition when *NO* was under greatest overburden.

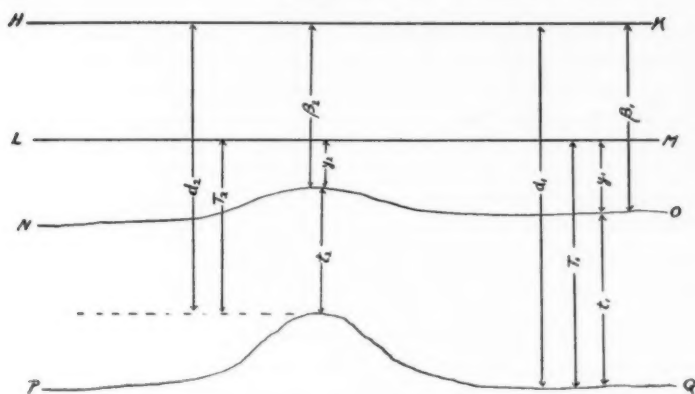


FIG. 5.—Ideal section over buried hill.

Case 1.

 β known, T not known

$$(B+A)y = \frac{A}{b} [1 + e^{-bd} - e^{-b(i+y)} - e^{-b\beta}] \quad (1)$$

Approximate solution if $e^{-by} = 1 - by + \frac{(by)^2}{2}$

$$\text{Let } E = \frac{Ab}{2} e^{-bt}$$

$$F = [(A+B) - Ae^{-bt}] = \text{Density at depth "t"}$$

$$G = \frac{A}{b} [1 + e^{-bd} - e^{-b\beta} - e^{-bt}]$$

$$y = \frac{-F + \sqrt{F^2 + 4GE}}{2E}, \text{ or if } F^2 \text{ is large compared with}$$

$$4GE, \text{ then } y_2 = \frac{G}{F} \left(1 - \frac{G}{F^2} E\right) \quad (2)$$

Case 2.

 T known, β not known

$$(B + A)y = \frac{A}{b} [1 + e^{-bd} - e^{-bT} - e^{-b(d-T+y)}] \quad (3)$$

Approximate solution if $e^{-by} = 1 - by + \frac{(by)^2}{2}$

$$\text{Let } E = \frac{Ab}{2} e^{-b(d-T)}$$

$$F = A + B - Ae^{-b(d-T)} = \text{density at depth } d - T$$

$$G = \frac{A}{b} [1 + e^{-bd} - e^{-bT} - e^{-b(d-T)}]$$

$$y = \frac{-F + \sqrt{F^2 + 4GE}}{2E}, \text{ or if } F^2 \text{ is large compared with}$$

$4GE$, then

$$y = \frac{G}{F} \left(1 - \frac{G}{F^2} E \right) \quad (4)$$

To compute closures, a computation for a column off the ridge and for one over the peak of the ridge must be made. Let y_1 be the settling off the ridge and y_2 the settling over the ridge. After solving for y_1 and y_2 by equations (2) and (4) substitute these approximate values and solve again for y_1 and y_2 in equations (1) and (3). Then the closure is $D = y_1 - y_2$.

Case 3.

Given β_1 , β_2 , and d_1 to calculate $h = d_1 - d_2$

$$(a) \quad y_1 - y_2 = \beta_1 - \beta_2 = D \text{ where } D \text{ is known} \quad (5)$$

$$(b) \quad \text{Compute } y_1 \text{ using equation (1) or (2)}$$

$$(c) \quad \text{Then } y_2 \text{ can be calculated from (5)}$$

(d) In equation (1) or (2) the known quantities are y_2 , β_2 , and $t_2 = d_2 - \beta_2$

(e) Calculate d_2 using equation (1) or (2)

Calculation of d_2 using equation (1)

$$e^{-bd_2} \left[\frac{A}{b} - \frac{A}{b} e^{-b(y_2 - \beta_2)} \right] = [y_2 (A + B) - \frac{A}{b} + \frac{A}{b} e^{-b\beta_2}]$$

$$\text{Let } E = \left[\frac{A}{b} - \frac{A}{b} e^{-b(y_2 - \beta_2)} \right]$$

$$\text{and } F = \left[y_2 (A + B) - \frac{A}{b} + \frac{A}{b} e^{-b\beta_2} \right]$$

$$\text{Then, } e^{-bd_2} = \frac{F}{E}, \log \frac{F}{E} = -bd_2,$$

$$\therefore d_2 = \frac{1}{b} \log \frac{E}{F} \quad (6)$$

Table III shows the amount of closure which should develop as a result of compaction over buried hills of different heights. The values were derived from the preceding equations for computing closure. The table gives an idea of the relation between the height of the buried hill, the distance of a bed above the hill, the total depth to which the bed has been buried, and the closure on the bed. The chart also shows how rapidly closure resulting from compaction decreases with depth of burial, and why large deeply buried structures may not be in evidence at the surface.

In order to estimate what part of the closure in the different structures in northern Oklahoma may be due to compaction over buried hills, let us apply our data to a few known structures. At the Thomas pool,¹ in Kay County, Oklahoma, the erosion surface on the "Mississippi lime" is approximately 4,000 feet below the present surface and has a relief ranging from 600 to 700 feet. About 500 of the 650 feet of sediments

¹Stuart K. Clark, "Thomas Oil Field, Kay County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 643.

TABLE III
CLOSURE TABLE

Overburden	Height above Hill Crest														Height of H.H.
	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	
200	2.80	2.20	1.23	9.0	5.5	4.0	3.0	2.5	2.1	1.9	1.7	1.6	1.5	1.4	200
400	8.60	3.80	2.57	16.0	11.3	9.0	6.5	4.0	3.4	3.3	3.2	3.1	3.0	2.9	400
600	9.00	3.80	3.80	27.0	17.1	14.0	10.0	7.5	6.5	5.0	4.3	4.0	3.8	3.6	600
800	11.00	7.00	7.00	35.5	26.5	22.5	15.0	11.0	9.7	7.0	6.0	5.0	4.0	3.0	800
1000	13.40	8.70	6.00	44.0	34.5	25.5	20.0	14.5	12.0	9.0	7.0	7.0	7.0	7.0	1000
1200	16.9	10.0	6.0	53.0	40.0	30.0	24.0	18.0	15.0	12.0	10.0	10.0	10.0	10.0	1200
1400	19.2	11.0	7.0	62.0	48.0	38.0	32.0	26.0	23.0	19.0	17.0	17.0	17.0	17.0	1400
1600	20.70	12.0	8.0	71.0	57.0	47.0	41.0	35.0	32.0	28.0	26.0	26.0	26.0	26.0	1600
1800	22.30	13.0	9.0	80.0	66.0	56.0	50.0	44.0	41.0	37.0	35.0	35.0	35.0	35.0	1800
2000	24.00	14.0	10.0	90.0	76.0	66.0	60.0	54.0	51.0	47.0	45.0	45.0	45.0	45.0	2000
2200	25.80	15.0	11.0	100.0	87.0	77.0	71.0	65.0	62.0	58.0	56.0	56.0	56.0	56.0	2200
2400	27.70	16.0	12.0	110.0	98.0	88.0	82.0	76.0	73.0	69.0	67.0	67.0	67.0	67.0	2400
2600	29.70	17.0	13.0	120.0	109.0	99.0	93.0	87.0	84.0	80.0	78.0	78.0	78.0	78.0	2600
2800	31.80	18.0	14.0	130.0	120.0	110.0	104.0	98.0	95.0	91.0	89.0	89.0	89.0	89.0	2800
3000	34.00	19.0	15.0	140.0	131.0	121.0	115.0	109.0	106.0	102.0	100.0	100.0	100.0	100.0	3000
3200	36.30	20.0	16.0	150.0	142.0	132.0	126.0	120.0	117.0	113.0	111.0	111.0	111.0	111.0	3200
3400	38.70	21.0	17.0	160.0	153.0	143.0	137.0	131.0	128.0	124.0	122.0	122.0	122.0	122.0	3400
3600	41.20	22.0	18.0	170.0	164.0	154.0	148.0	142.0	139.0	135.0	133.0	133.0	133.0	133.0	3600
3800	43.80	23.0	19.0	180.0	175.0	165.0	159.0	153.0	150.0	146.0	144.0	144.0	144.0	144.0	3800
4000	46.50	24.0	20.0	190.0	186.0	176.0	170.0	164.0	161.0	157.0	155.0	155.0	155.0	155.0	4000
4200	49.30	25.0	21.0	200.0	197.0	187.0	181.0	175.0	172.0	168.0	166.0	166.0	166.0	166.0	4200
4400	52.20	26.0	22.0	210.0	208.0	198.0	192.0	186.0	183.0	179.0	177.0	177.0	177.0	177.0	4400
4600	55.20	27.0	23.0	220.0	219.0	209.0	203.0	197.0	194.0	190.0	188.0	188.0	188.0	188.0	4600
4800	58.30	28.0	24.0	230.0	230.0	220.0	214.0	208.0	205.0	201.0	199.0	199.0	199.0	199.0	4800
5000	61.50	29.0	25.0	240.0	241.0	231.0	225.0	219.0	216.0	212.0	210.0	210.0	210.0	210.0	5000
5200	64.80	30.0	26.0	250.0	252.0	242.0	236.0	230.0	227.0	223.0	221.0	221.0	221.0	221.0	5200
5400	68.20	31.0	27.0	260.0	263.0	253.0	247.0	241.0	238.0	234.0	232.0	232.0	232.0	232.0	5400
5600	71.70	32.0	28.0	270.0	274.0	264.0	258.0	252.0	249.0	245.0	243.0	243.0	243.0	243.0	5600
5800	75.30	33.0	29.0	280.0	285.0	275.0	269.0	263.0	260.0	256.0	254.0	254.0	254.0	254.0	5800
6000	79.00	34.0	30.0	290.0	296.0	286.0	280.0	274.0	271.0	267.0	265.0	265.0	265.0	265.0	6000
6200	82.80	35.0	31.0	300.0	307.0	297.0	291.0	285.0	282.0	278.0	276.0	276.0	276.0	276.0	6200
6400	86.70	36.0	32.0	310.0	318.0	308.0	302.0	296.0	293.0	289.0	287.0	287.0	287.0	287.0	6400
6600	90.70	37.0	33.0	320.0	329.0	319.0	313.0	307.0	304.0	300.0	298.0	298.0	298.0	298.0	6600
6800	94.80	38.0	34.0	330.0	340.0	330.0	324.0	318.0	315.0	311.0	309.0	309.0	309.0	309.0	6800
7000	99.00	39.0	35.0	340.0	351.0	341.0	335.0	329.0	326.0	322.0	320.0	320.0	320.0	320.0	7000
7200	103.30	40.0	36.0	350.0	362.0	352.0	346.0	340.0	337.0	333.0	331.0	331.0	331.0	331.0	7200
7400	107.70	41.0	37.0	360.0	373.0	363.0	357.0	351.0	348.0	344.0	342.0	342.0	342.0	342.0	7400
7600	112.20	42.0	38.0	370.0	384.0	374.0	368.0	362.0	359.0	355.0	353.0	353.0	353.0	353.0	7600
7800	116.80	43.0	39.0	380.0	395.0	385.0	379.0	373.0	370.0	366.0	364.0	364.0	364.0	364.0	7800
8000	121.50	44.0	40.0	390.0	406.0	396.0	390.0	384.0	381.0	377.0	375.0	375.0	375.0	375.0	8000
8200	126.30	45.0	41.0	400.0	417.0	407.0	401.0	395.0	392.0	388.0	386.0	386.0	386.0	386.0	8200
8400	131.20	46.0	42.0	410.0	428.0	418.0	412.0	406.0	403.0	399.0	397.0	397.0	397.0	397.0	8400
8600	136.20	47.0	43.0	420.0	439.0	429.0	423.0	417.0	414.0	410.0	408.0	408.0	408.0	408.0	8600
8800	141.30	48.0	44.0	430.0	450.0	440.0	434.0	428.0	425.0	421.0	419.0	419.0	419.0	419.0	8800
9000	146.50	49.0	45.0	440.0	461.0	451.0	445.0	439.0	436.0	432.0	430.0	430.0	430.0	430.0	9000
9200	151.80	50.0	46.0	450.0	472.0	462.0	456.0	450.0	447.0	443.0	441.0	441.0	441.0	441.0	9200
9400	157.20	51.0	47.0	460.0	483.0	473.0	467.0	461.0	458.0	454.0	452.0	452.0	452.0	452.0	9400
9600	162.70	52.0	48.0	470.0	494.0	484.0	478.0	472.0	469.0	465.0	463.0	463.0	463.0	463.0	9600
9800	168.30	53.0	49.0	480.0	505.0	495.0	489.0	483.0	480.0	476.0	474.0	474.0	474.0	474.0	9800
10000	174.00	54.0	50.0	490.0	516.0	506.0	500.0	494.0	491.0	487.0	485.0	485.0	485.0	485.0	10000

now surrounding the buried hill are compressible shales or sandy shales, the remainder being mostly limestone. At 3,500-4,000 feet depth of burial at Thomas, compaction amounts to more than 45 per cent of the original volume of shale; hence, the original proportion of shale to limestone in the 650 feet surrounding the buried hill was about 10 to 1, or approximately 600 feet of shale. Closure on the Layton sand at $\pm 3,400$ feet is about 200 feet; on the Pawhuska limestone at 2,100 feet, it is approximately 70 feet. Closure on the surface beds amounts to about 30 feet. From the closure chart we find that the Layton sand, with an overburden of 5,400 feet and lying 600 feet above a 600-foot hill, should have a closure due to differential settling alone of approximately 160 feet. Similar computation for the Pawhuska limestone 2,000 feet above the 600-foot hill and under 4,000 feet overburden gives 69 feet of closure. Computed surface structure due to settling is 18 feet.

At Pershing, Oklahoma, the "Mississippi lime" formed an island in Pennsylvanian seas. The buried hill is now about 2,075 feet below the surface formation, the Elgin sand, which has a closure of 10-30 feet. Density measurements suggest that about 3,500 feet of sediments have once covered the present surface beds. The height of the buried hill is approximately 200 feet. If it is assumed that the hill was surrounded by sediments including 150 feet of shale, the structure developed in the Elgin sand by differential settling is 18 feet, as calculated by the preceding equations.

The writer does not wish to imply that the entire structure at Thomas or Pershing or any other structure in the Mid-Continent field is due to compaction of sediments over a buried ridge, but without question, a very considerable part must be due to that cause. Undoubtedly, part of the structure is due to the original attitude of the beds at the time of their deposition on the uneven ocean floor. Particularly is this true for the deeper beds. That computed closure caused by compaction is always less than observed closure is partly accounted for by the fact that the beds had some closure at the time of their deposition and before compaction became operative. Furthermore, in some places excessive thicknesses of lenticular sand may occur, which, because of the different compressibility of sand and shale, further accentuate the structure. In many places there is also evidence of post-Mississippian movement, especially along faults, and either continual or intermittent differential settling of the basement occurred throughout most of Permian and Pennsylvanian time.

RELATION OF COMPACTION IN SEDIMENTS TO EARTH STRESSES AND
PALEOGEOGRAPHY

Not enough work has as yet been done on the problem of compaction in sediments to warrant definite statements as to the nature and extent of information that can be gained concerning the history of a region from compaction studies. It is probable that some idea concerning the transmission of stresses through sediments may be gained by a careful study of densities or porosities of shale in and around areas of intense folding. It would be expected, however, that the stresses which are transmitted through any considerable distance must be carried by the more resistant and deeper basement rocks. Since intense diastrophic movements are considered to have definitely altered the carbon ratio in coal, a corresponding change might be expected to occur in the degree of compaction in accompanying shales. Also, in areas where there has been a relative upward movement, there may be measurable differences in compaction which definitely locate such movements.

The compaction noted by Hedberg in Hamilton County, Kansas, is much less per thousand feet of burial than that observed by the writer in Kay, Noble, and Garfield counties, in Oklahoma. Either there were inherent differences in the character of the sediments in the two areas which cause their compressibilities to differ, or some other factors, such as the age of the formations or the nearness to centers of folding, cause the difference. This question must be answered by comparing the results of compaction studies in many different areas, including, especially, areas of young sediments where there has been relatively little erosion.

In many areas there is very little evidence concerning the thickness and extent of sediments which may once have covered the strata now exposed at the surface. If a definite relationship were established between compaction and depth of burial, it would be possible to determine the maximum depth to which shales in any undisturbed area had once been buried.

If it is granted that the compaction depth relations in north-central Oklahoma are approximately correct as given in this paper, then about 1,400 feet of Permian and younger sediments once covered the area around Garber, Oklahoma, nearly 2,000 feet were present at Thomas and Tonkawa, and 2,400-2,500 feet at Ponca City.

By applying the compaction-depth data derived from the areas just named to the Nowata-Chelsea district southeast of Bartlesville, Oklahoma, where densities range from 2.47 to 2.51 at depths ranging from 150 to 400 feet in the lower Pennsylvanian, it is estimated that the eroded

overburden is 4,000-4,500 feet. These figures indicate that the total stratigraphic thickness deposited above the Oswego limestone in the lower part of the Pennsylvanian was 1,000-1,500 feet less at Chelsea than at Garber.

COMPACTION AND OIL MIGRATION¹

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ABSTRACT

The primary cause of the movement of oil from a shale source bed to reservoir beds is compaction within the shale beds. Reservoir beds such as limestones and sandstones show little compaction in comparison with shale. Compaction in shale always occurs when there is an increase in the depth of burial and causes an outward movement of the fluid content of the shale toward adjacent non-compressible horizons of lower pressure or with easier outlet to the surface.

Compaction in shale may be expressed as an exponential function of the depth of burial, and continues to be operative to an appreciable extent at depths ranging from 3,000 to 4,000 feet.

Zonal migration of fluid as caused by compaction may help explain the variation in composition of waters at different depths.

Temperature changes, buoyancy, and capillarity are not effective in causing oil migration if the oil is in a disseminated state, or adsorbed on the mineral grains, or associated with free gas in bubbles.

INTRODUCTION

The geological literature is replete with papers concerning the origin, migration, and accumulation of oil. Bibliographies of the subject are so numerous that references to only a few of the many excellent papers are given here. Probably most of the ideas of American geologists concerning the genesis of oil pools are outlined in a review by McCoy.³ A paper by Ernest Clark⁴ very ably presents the English conception.

AGENCIES EFFECTIVE IN CAUSING MIGRATION

The agencies which may be instrumental in controlling the movement of oil in buried sediments are heat, pressure, and the physical characteristics of associated fluids. The effects of these agencies are

¹Manuscript received by the editor, September 7, 1929.
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³A. W. McCoy, "A Brief Outline of Some Oil Accumulation Problems," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 1015.

⁴Ernest Clark, "Organic Theories of Oil Origin," *Jour. Inst. Petrol. Tech.*, Vol. 12 (June, 1926), p. 257.

noticed in (1) temperature changes and the consequent expansion and changes in viscosity and specific gravity, (2) buoyancy, due to differences in the specific gravity of oil, gas, and associated water, (3) capillarity and molecular forces operative between oil and water, and (4) the action of circulating water.

The facility and thoroughness with which these agencies may remove oil from a sediment depend on three factors: (1) the state of dissemination of the oil in a sediment, (2) its association with water and free gas, and (3) its ability to adhere to sedimentary grains. Whether or not the major part of the oil in a sediment may be removed by these agencies depends on whether the forces tending to cause the migration are stronger or weaker than the forces of adhesion and resistance to flow inherent in the oil under the environmental conditions in the sediment. It is shown in this paper that after most of the oil is removed, the migration of the remaining films is merely a matter of time and prolonged association with water.

EFFECT OF TEMPERATURE CHANGES

Except in merely local areas of intense igneous activity and diastrophic movements, the influence of temperature changes is very small. In areas where oil is plentiful, temperatures ranging from about 60° to 160° F. have been observed at depths not exceeding 5,500 feet. There is no reasonable evidence for thinking that temperatures in the sedimentary strata of oil fields should ever have been very different from what they are to-day. The expansion and changes in specific gravity of oil and water due to changes in temperature within the limits heretofore given would not be of much consequence in moving oil. The forces due to the expansion of associated gas might be considerable, but, as the temperature changes are very slow and not frequently recurrent, they can not be of importance in this connection.

EFFECT OF BUOYANCY

Buoyancy is expressed by the difference in specific gravity of oil and the associated water. The effective buoyancy is altered by the amount of gas occurring in the sediment. Gas associated with the oil alters its specific gravity and fluidity, but the presence of free gas disseminated throughout a partly oil-saturated sediment may actually prevent the flow of the oil under certain conditions.¹ An unbroken

¹C. W. Cook, "The Study of Capillary Relationship of Oil and Gas," *Econ. Geol.*, Vol. 18 (1923), p. 167.

column of oil is more easily forced through capillary openings than is a series of drops of oil separated by gas bubbles.¹ There is much controversy about the importance of buoyancy in migration, but the general opinion seems to be that its effectiveness depends upon the state of dissemination of the oil. Large bodies of oil may move upward, by buoyancy, in a water-soaked sand of suitable texture, whereas tiny drops may not, because, in a larger body, the resistance to flow due to surface energies is less per unit volume of oil. In a similar way, the size of the pores determines the amount of surface resistance, so that in a sufficiently fine sediment buoyancy may be very ineffective in causing migration. There is, perhaps, little doubt that migration of large bodies of oil in fairly coarse oil sands is, to some extent, if not chiefly, due to buoyancy. In sediments such as constitute shale source beds, if the oil is in a disseminated state of droplets and stringers, or if it is associated with free gas, buoyancy can not be effective in causing the oil to move out of the shale.

CAPILLARITY AND MIGRATION

The effectiveness of capillarity in oil migration has been discussed by McCoy,² Cook,³ Skirvin,⁴ Mills,⁵ Russell,⁶ and others. One group led by McCoy believes that it is the principal cause, although others would assign it only a very small part and believe that capillarity may tend to prevent movement.

In a discussion of migration of oil in sediments from this angle, the same factors that were cited previously are concerned, namely, texture of the sediments, association of oil, water, and gas, the state of dissemination of the oil, and the extent to which the oil is adsorbed on the sediment. Due to the difference in surface energies between oil and sand, and water and sand, it has been postulated that water will displace oil from fine sediment to coarse.⁷ This is termed selective capillarity.

¹This is the much discussed "Jamin Effect." See series of articles by Stanley Herold in the *Oil and Gas Journal* (1924-27).

²A. W. McCoy, "Some Effects of Capillarity on Oil Accumulation," *Jour. Geol.*, Vol. 24 (1916), p. 798.

³C. W. Cook, "Study of Capillary Relationship of Oil and Gas," *Econ. Geol.*, Vol. 18 (1923), p. 167.

⁴O. W. Skirvin, "Experimental Study of the Invasion of Oil into a Water-Wet Sand," *Econ. Geol.*, Vol. 17 (1922), p. 461.

⁵R. van A. Mills, "Experimental Studies of Subsurface Relationships of Oil and Gas," *Econ. Geol.*, Vol. 18 (1923), p. 167.

⁶W. L. Russell, "Some Experiments on Capillarity and Oil Migration," *Econ. Geol.*, Vol. 19 (1924), p. 35.

⁷A. W. McCoy, *op. cit.*

Considerable experimentation has been carried on in the laboratory on the subject of capillarity and oil migration,¹ but one very important fact has been overlooked in preparing and interpreting these experiments; that is, the oil which was displaced probably never had been adsorbed directly on the sand grains; an adsorbed film of water existed between the sand and oil. Clean sand exposed to the atmosphere retains an adsorbed film of moisture which, according to Nutting,² is about 20 molecules or 10^{-6} centimeters thick. Unless this film is removed, oil does not adhere directly to the sand grain. Experiments performed by the writer and his associates³ indicate that if this water film is not removed before the sand is saturated with oil, selective capillarity is operative, as stated by McCoy and others. However, if the sand or shale is first thoroughly dried and then saturated with oil so that the oil is adsorbed freely by the sand or shale, then selective capillarity is not operative. (Experimenters should bear this in mind when studying oil recovery.)

The experiments conducted by the writer were somewhat similar to those performed by McCoy and Russell. The upper halves of quart bottles were used. Glass tubes were inserted about one inch into the bottles through rubber stoppers. The oil-saturated sediment was packed into the bottle around the glass tube. A little water-wet sand was placed in the lower open end of the bottle and the whole was placed upright in a beaker of water. The water in the beaker just covered the cork in the bottle. When selective capillarity was operative the water exerted a pressure on the oil and forced it up in the glass tube. The shale used in the experiments was ground to pass through an 80-mesh sieve. The sand used was the St. Peter. It was slightly coarser than the average "Wilcox" sand. To remove the adsorbed water, the sediment was held at red heat for 20 minutes and cooled in a desiccator.

These results show conclusively the effect of removing the moisture and allowing the oil to adhere directly to the sand grain. The indicated rise in inches must not be taken quantitatively, as it does not represent the maximum pressure which might develop. When the heights indicated were attained, the back pressure due to the weight of the column in the tube was sufficient to cause the oil to migrate downward to the bottom of the bottle and escape, thereby establishing a balance.

¹A. W. McCoy, C. W. Cook, O. W. Skirvin, W. L. Russell, *op. cit.*

²P. G. Nutting, "The Movement of Fluids in Porous Solids," *Jour. Franklin Inst.*, Vol. 203 (1927), p. 317.

³Bruno Petsch and Raymond Stevenson, of the Marland Research Department.

TABLE I
RESULTS OF CAPILLARITY EXPERIMENT

	Rise in Inches	
	Min.	Max.
Untreated sand, oil saturated, in distilled H_2O	2½	5½
Dried sand, oil saturated, in distilled H_2O	0	0
Untreated sand, oil saturated, in salt water	2½	5½
Dried sand, oil saturated, in salt water	0	0
Untreated sand, oil saturated, in Na_2CO_3 solution	2¾	3
Dried sand, oil saturated, in Na_2CO_3 solution	0	0
Untreated shale, oil saturated, in distilled H_2O	42	47
Dried shale, oil saturated, in distilled H_2O	0	0

In this experiment the sand and shale were saturated at atmospheric pressure. The idea next came to mind that perhaps this adsorbed moisture would be absorbed if the untreated sand was saturated with oil under a high pressure. To test this possibility, untreated sand was placed in an oil bath under 1,500 pounds pressure for two days and then the selective capillarity was tested as in the previous experiments. No rise of the oil in the tube was noticed until after two days and then it was very slow, whereas in a normal run, saturated at atmospheric pressure, a height of more than 2½ inches was always reached in less than ½ hour. This suggests that in time oil under pressure would totally absorb the adsorbed water film. Such absorption under pressure accounts for the thoroughness with which oil has become adsorbed on the sand in natural pools.

It is an established fact that capillarity is more effective in a fine-grained medium than in a coarse medium. A similar rule holds for selective capillarity. Under the most favorable conditions existing in an average oil sand, pressures due to selective capillarity are equivalent to only a few inches of water head, whereas in a compact shale saturated with oil and surrounded with water, the pressure amounts to several feet.

If conditions in a sediment are such that the oil is not adsorbed on the mineral grains, and the texture is suitable, the extent to which selective capillarity may act is determined by the state of dissemination of the oil and the amount of free gas. These factors increase the resistance to flow and can entirely stop capillary movement.¹ In order that capillarity alone may cause migration from a source bed, the shale must

¹C. W. Washburne, *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 50 (1914).
C. W. Cook, *op. cit.*, p. 171.

be nearly saturated with oil and in contact with a coarser sediment saturated with water. No additional fluid may enter the two beds of unlike textures; the oil and water may merely exchange places. If the oil were scattered in drops or small isolated bodies in a water-wet shale, capillarity could not displace it. McCoy states in his review of some oil accumulation problems that

One suggestion which is brought out by this interpretation of oil and water relations in small openings is that the source beds would have to be fairly well saturated with oil in order to expect replacement of quantity into the reservoir zones. Small amounts of oil disseminated throughout a shaly horizon when acted upon by water would tend to spread out in a series of drops into water capillaries, and unless there was additional oil-soaked shale immediately adjoining for the water to work on there would be no reason why these oil stringers would move on toward the sand.

COMPACTION AND MIGRATION

The last and most important agent in causing the movement of oil in buried strata is circulating water. Rich¹, Shaw², Daly³, and Munn⁴ discuss the circulation of underground water and its relation to oil accumulation. But as a prerequisite to circulation, there must be a difference in pressure on different parts of the water column. Where does the excess water come from, and where does it go? Also, if there is a more or less connected system of circulation throughout the sediments, why the great variation in composition of waters from different sands? Circulation of water analogous to artesian circulation is known to have occurred in some oil field areas such as California, but circulation in a direction parallel with the bedding must not be confused with circulation across and through the beds. The former is confined to the beds having a high permeability, chiefly sands; therefore, it is an agent causing migration in the reservoir beds, but not in the tight shale source beds; the latter type of circulation across the bedding is necessary in order to drive oil from the source beds and into the porous reservoir beds. Underground circulation due to differences in hydrostatic head and supplied by surface waters admitted at the outcrop will be confined to the porous con-

¹John L. Rich, "Moving Underground Water as a Primary Cause of Migration and Accumulation of Oil and Gas," *Econ. Geol.*, Vol. 16 (1921), p. 347.

²E. W. Shaw, "The Role and Fate of Connate Waters in Oil and Gas Sands," *Amer. Inst. Min. Met. Eng. Bull.* 103 (1915), pp. 1449-59.

³M. R. Daly, "The Diastrophic Theory," *Amer. Inst. Min. Met. Eng. Bull.* 115 (1916), p. 1137.

⁴M. J. Munn, "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," *Econ. Geol.*, Vol. 4 (1909), p. 141.

tinuous beds or to the beds which offer least resistance to flow. Forces causing water to move through tight shale beds must originate in the shale itself. There are two very definite agents which may develop differences in water pressure at various points in buried strata so that circulation in the more impervious beds is imperative. They are (1) diastrophic movements and (2) compaction of sediments. The former are spasmodic and local; the latter is continuous and general.

Daly urges that at times of diastrophic movements, fluids are forced from zones of greatest compression and gathered into zones of low compression or tension, as on crests of folds. It seems certain that some movements of fluids would be caused by such disturbances, but little quantitative information is available. It is not probable that much compression or tension was developed during the formation of the oil-bearing structures in the Pennsylvanian and Permian strata in the Mid-Continent area, because these structures are due chiefly to deposition and subsequent differential settling of the sediments themselves and of the basement rock.

On the contrary, the compaction of sediments due to increasing overburden is definitely known to occur, and it must force out any fluids existing in the compressible strata. Definite and positive data have been obtained by the writer on the relative amount of compaction in sediments buried to different depths. Hedberg¹ has furnished some excellent data on the subject, but he was handicapped by not having access to enough samples. The writer, assisted by Bruno Petsch and Raymond Stevenson, has studied the physical properties of the sediments of northern Oklahoma since the spring of 1926. During this time the relative amount of compaction as expressed in changes of bulk density and porosity has been measured for more than 2,200 samples.

As a result of these studies, compaction of shales is found to be a logarithmic function of the depth of burial. The curve in Figure 1 shows this relation in northern Oklahoma.

At or near the surface, freshly deposited clay has a bulk density of 1.4-1.5 grams per cubic centimeter and a porosity of 45-50 per cent. At 6,000 feet the average density of shale is about 2.6 and the porosity approximately 5 per cent. Compaction equivalent to more than 20 per cent of the original volume has occurred by the time the clay has been buried 1,000 feet, 35 per cent at 2,000 feet, and 40 per cent at 3,000 feet. Of the amount of fluid originally in a saturated clay at the surface,

¹H. D. Hedberg, "The Effects of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), p. 1035.

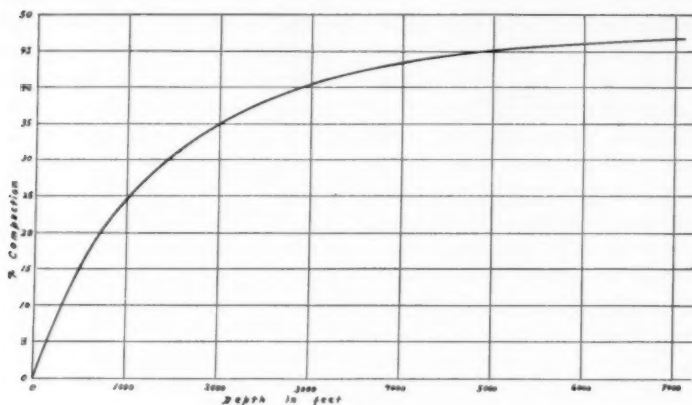


FIG. 1.—Compaction-depth curve.

about 50 per cent is squeezed out at 1,000 feet depth of burial, 70 per cent at 2,000 feet, 85 per cent at 4,000 feet, and more than 90 per cent at 6,000 feet.

It is evident that most compaction does not occur within the first few hundred feet of the surface, as many authors have thought. The compaction of a shale at 1,000 feet is about half what it is at 6,000 feet. In other words, shales can be very considerably compressed even after having been buried 2,000 feet, or as deep as 3,000 feet. These data prove that enormous quantities of water are forced out of compacting beds by the weight of the overburden, and this outward movement of water is continuous throughout all geologic periods of deposition which increase the weight of the overburden.

As the effect of compaction is felt in the sediments from the time of deposition onward, there must be an almost continuous movement of fluids in all compressible beds toward the non-compressible and incompletely saturated beds, or toward those beds furnishing easiest outlet to the surface or relief from pressure.

Density and porosity determination as well as compaction tests in the laboratory show that sands are very slightly compressible in comparison with shale. A study of sandstone samples from deep wells showed no measurable increase in density with greater depth of burial. Most of the compaction in sand is due to rearrangement and closer spacing of grains, and occurs soon after deposition. Therefore, liquids or gases which a deeply buried sand contains are not under pressure developed

by compaction in the sand itself, but by compaction in the surrounding shale beds. Subsidence in areas such as the Goose Creek field, Texas, or the maintenance of hydraulic head in such well known aquifers as the Dakota sandstone may be satisfactorily explained by compaction in the associated shales.

Compaction of source beds forces out all oil and gas which are not firmly adsorbed to the grain surfaces. The continual shifting, breaking, granulation, and bending of particles in an effort to occupy a smaller volume under pressure break up and rub off much of the oil film adhering to the grains.

Another cause, which may be effective in forcing out oil where the volume of oil is small, the volume of water large, and the interfacial area between oil and water large (as where only thin films of oil remain on a water-saturated sediment) is absorption. Continuous molecular bombardment between the small amount of oil and the large amount of water may finally result in the complete removal of the oil from the surface of the grain.

If the upper 10 feet of a 50-foot shale bed contains oil and is overlain by a porous sand bed which serves as an outlet for fluids squeezed from the shale, calculation shows that by the time the bed has been buried 1,000 feet, more than 40 times as much fluid has passed through each foot of the upper 10 feet of shale as still remains in it. Inasmuch as the shale particles are shifting their position as they settle, and as molecular bombardment may be especially effective in the latter stages, it is very probable that the shale would be thoroughly cleaned of its oil.

The circulation of fluids due to compaction of sediments and final absorption of small amounts of oil by large quantities of passing water seems to be the best explanation of the migration of oil from possible source beds.

When the oil reaches the sand reservoir bed, it is carried along by the same force which drove it from the source bed, influenced somewhat by the differences of hydrostatic head which may exist in the sand. Buoyancy is effective now that the oil and gas are in motion in water, and causes the final accumulation of part of the oil in the higher traps in the sand.

This explanation of a slow, continuous circulation in deeply buried strata may explain the variations in chemical constituency between waters of different sands. As there is an adjustment of mineral grains going on during the settling, the fluids are squeezed out and into the nearest sandstone outlet. There should be as many individual zones

of circulation as there are outlet beds, and each zone might carry fluids of different chemical constituency.

CONCLUSION

The effectiveness of any agent in causing the migration of oil in buried sediments is determined by certain conditions, chief of which are: (1) the gravity and viscosity of the oil; (2) the physical character of the sediment; (3) the state of association of oil, free and adsorbed gas, and water; (4) the state of dissemination of oil, gas, and water in the sediment; and (5) the adsorption or lack of adsorption of the oil on the grains of the sediment in which it occurs.

Temperature changes as a cause of oil migration are of little importance. Temperature is indirectly of importance in that it determines to some extent the gravity and fluidity of the oil.

Buoyancy is operative in reservoir sands while the fluid is being moved along by other forces, and causes oil and gas to seek the higher parts of the bed. It is not instrumental in migration if the oil is in fine sediment, or is finely disseminated, or is associated with free gas in the form of bubbles, or if the oil is adsorbed on the sedimentary grains.

Capillarity is effective in moving oil short distances from a fine sediment to an adjoining coarse sediment, provided the fine sediment is thoroughly saturated with oil and the oil is not adsorbed to the surface of the grains. If the oil is in a disseminated state, or adsorbed on the sediment, or is associated with free gas in bubbles, capillarity is not effective.

Movement of oil out of a source bed is more or less in a direction across the bedding, whereas migration in a reservoir bed is mostly parallel with the bedding. Migration is not caused by the same force in both cases. Circulation of buried water analogous to artesian circulation is in a direction parallel with the bedding and follows the paths of least resistance through the most continuous and permeable beds, which are commonly reservoir beds. Such circulation fed by surface waters admitted at the outcrop is not operative to any appreciable extent in shale beds, but is a factor in causing oil migration within reservoir beds in some localities. Migration of oil from source beds to reservoir beds is due chiefly to circulating water, the circulation in some beds being partly due to diastrophic movements, as postulated by Daly, but ordinarily due to the compaction of sediments under the weight of the overburden. Circulation due to compaction in shale is positive; it is applicable to all compressible sediments, and definitely displaces all interstitial oil and much

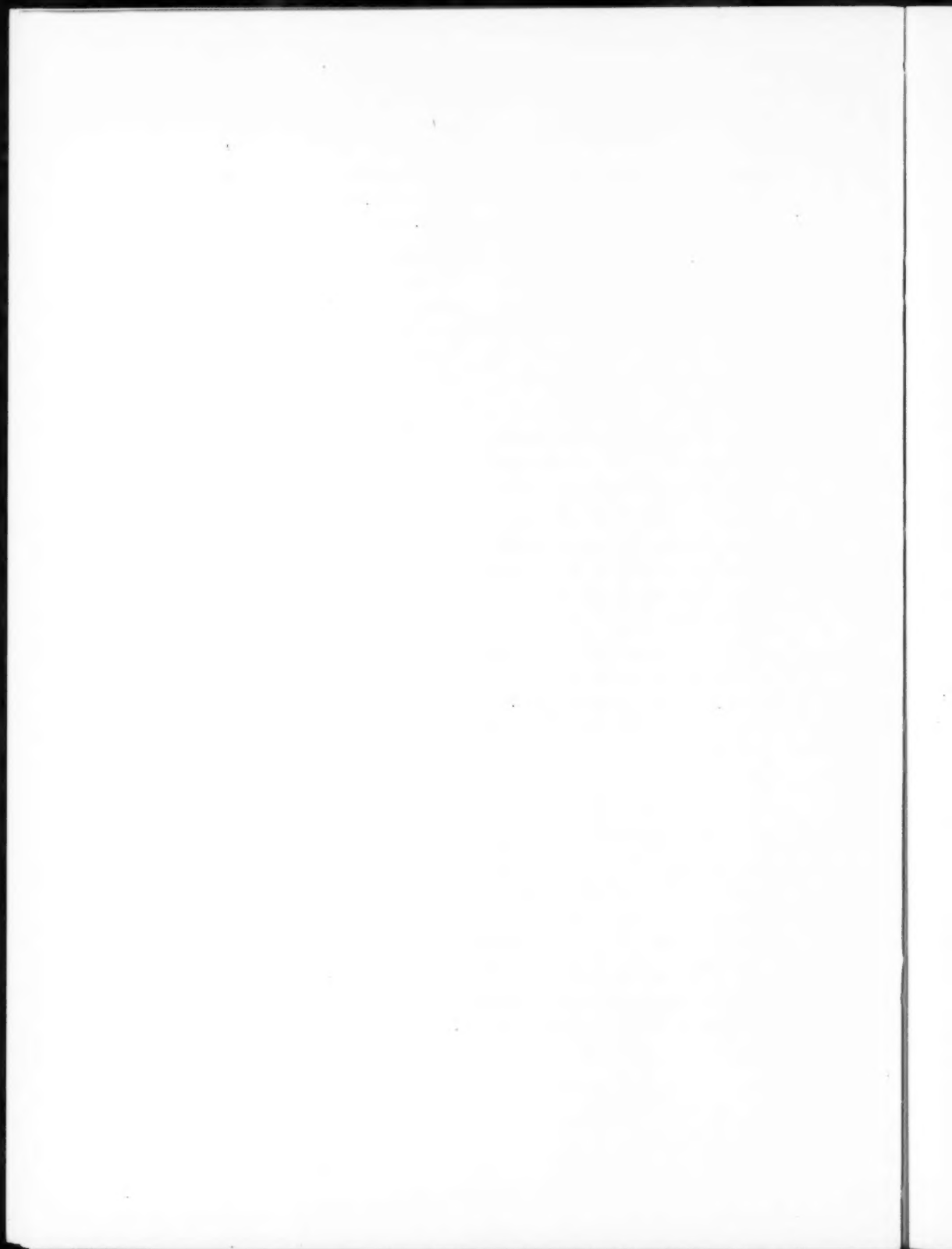
of the adsorbed films. Circulation due to these same forces continues in the reservoir bed and is also a cause of oil migration there.

Compaction in shale is a logarithmic function of the depth of burial, and circulation due to compaction is shown by experimental data to continue to be operative in sediments after they have been buried several thousand feet.

This interpretation of underground circulation accounts for the variation in chemical character of waters in different sands, as there should be as many individual zones of circulation as there are outlet beds, and each zone might carry fluids of different chemical constituency.

Absorption of oil by water due to molecular bombardment is probably instrumental in removing the oil films from sedimentary grains in the latter stages of oil displacement by circulating waters.

It is evident that to understand exactly how oil has migrated it is necessary to understand the conditions under which it is formed. If oil was formed from organic matter in shale by a very slow process, at any time after the shale was deposited, the oil probably was disseminated in drops and stringers in water, there probably was associated free gas, and the oil may or may not have been adsorbed to the sediment in which it was formed. All of these factors are of great importance in explaining the migration of oil from its source to its present location in pools. Irrespective of the part played by other agencies, compaction has taken place in any source bed and has therefore been one cause of the migration of fluids present in the source beds, not only during periods when the overburden was increasing, but also at any time that there may have been an effective lowering of the hydrostatic pressure on the interstitial fluids.



STRUCTURE AND STRATIGRAPHY OF SOUTHWESTERN OKLAHOMA¹

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ABSTRACT

The writer discusses the Wichita uplift, and its relation to adjacent producing oil and gas structures in southwestern Oklahoma. Cross sections illustrate the stratigraphy of the oil and gas horizons of the producing fields, and the possibilities for deeper production, as indicated by a study of the older sediments exposed by the truncation of the Wichita uplift. The writer outlines undeveloped regionally favorable structural areas, and as a guide to structural mapping and correlations describes and illustrates transitions in the stratigraphy of the Permian.

ACKNOWLEDGMENTS

The writer has been greatly assisted in the correlation of the base of the Duncan with the base of the Flower Pot by Nelson B. Potter and G. E. Anderson, geologists for the Indian Territory Illuminating Oil Company. He also acknowledges the assistance of Roger W. Sawyer, Sherwood Buckstaff, H. F. Schweer, Frank C. Greene, Otto E. Brown, L. D. Bartell, and many other geologists with whom he has discussed these problems. But in the assembling of the data included in this paper, and for the detail work required he is especially indebted to the following men who have been associated with him during the past seven years: Allan B. Gray, Waldemar M. Ervin, P. A. Wallace, Fred Brasted, Jr.; and to L. J. Fulton and Murray Wells, his present associates.

WICHITA MOUNTAINS

The Wichita Mountains constitute the dominant structural feature of southwestern Oklahoma. The Wichita uplift is expressed by three *en echelon* ridges of typical acidic granite which strike approximately N. 60° W. These ridges are here referred to as the Northeast, Central, and Southwest ridges (Fig. 1). The Northeast ridge, as shown by exposures, extends from the southeast corner of Sec. 21, T. 4 N., R. 12 W., Comanche County, northwest to Sec. 8, T. 6 N., R. 14 W., Kiowa

¹Read before the Association at the Fort Worth meeting, March 21, 1929. Manuscript received by the editor, September 18, 1929.

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AREAL GEOLOGY OF THE WICHITA MOUNTAINS

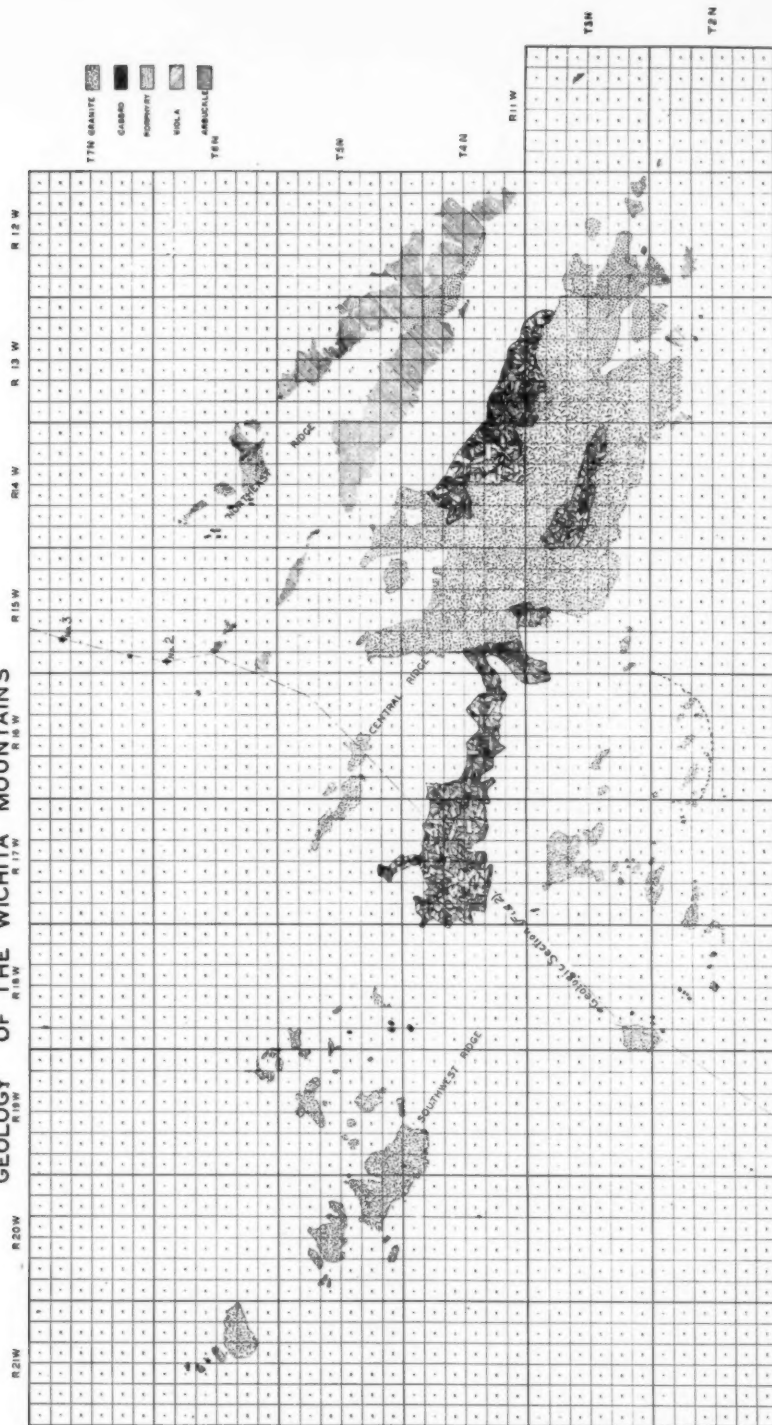


FIG. 1.—Areal geology of Wichita Mountains, showing igneous ridges. Scale: 1 township = 6 miles. For names of wells on line of geologic section, see Figure 2.

County. The Central ridge extends from Fort Sill, Sec. 8, T. 2 N., R. 11 W., Comanche County, northwest to Sec. 10, T. 5 N., R. 17 W., Kiowa County. The Southwest ridge extends from the central part of T. 2 N., R. 16 W., Kiowa County, northwest into Sec. 8, T. 6 N., R. 21 W., Greer County.

The Northeast ridge is a faulted anticline, with a core of porphyritic granite which is exposed all along the axis. This granite core is flanked on the north by a full section of the Arbuckle limestone and the underlying Reagan sandstone, but on the south flank the Arbuckle limestone indicates a fault of about 2,000 feet, as approximately only the upper 4,000 feet of the Arbuckle limestone is exposed. The downthrow of this fault is on the south, toward the deep syncline which separates the Northeast ridge from the Central ridge. The exposed width of the igneous core of the Northeast ridge ranges from $\frac{1}{4}$ mile to 1 mile.

The Central ridge consists almost entirely of red granite. Its width ranges from 6 to 10 miles in the central and southeastern parts, but is only approximately 1 mile wide at the northwestern extremity northwest of the town of Cooperton, Kiowa County. This ridge is in contact with the sedimentary formation only along the southeastern extremity and for approximately 20 miles along the northeastern flank. The sedimentary formation exposed is the Arbuckle limestone.

The Southwest ridge is nowhere in contact with the pre-uplift sedimentary formation. Above the surface this ridge is approximately 40 miles in length and ranges in width from 1 to 12 miles.

The syncline between the Northeast ridge and the Central ridge is a structural feature worthy of description. Although it is not more than 8 miles in width, a study of the exposed Arbuckle and Viola limestones and the log of Johnston-McDowell's Wedels No. 1 drilled in Sec. 6, T. 6 N., R. 15 W., Kiowa County, proved the depth of this syncline to be 8,000 feet (Fig. 2). The syncline is here termed the Rainy Mountain syncline because that mountain is near its axis.

INTRUSIONS

The acidic or red granites of the Wichita uplift have been intruded by basic magmas, which crystallized as peridotites and gabbros. There are three major basic intrusions now exposed in the Wichitas. One is in the center of the present Wichita Forest and Game Preserve; another is north of the preserve, and extends along the north side of Mt. Sheridan and Mt. Wall and northwestward a distance of 10 or 12 miles to Saddle Mountain. These two intrusions are in Comanche County. The third is in the vicinity of the town of Cold Springs, and extends from

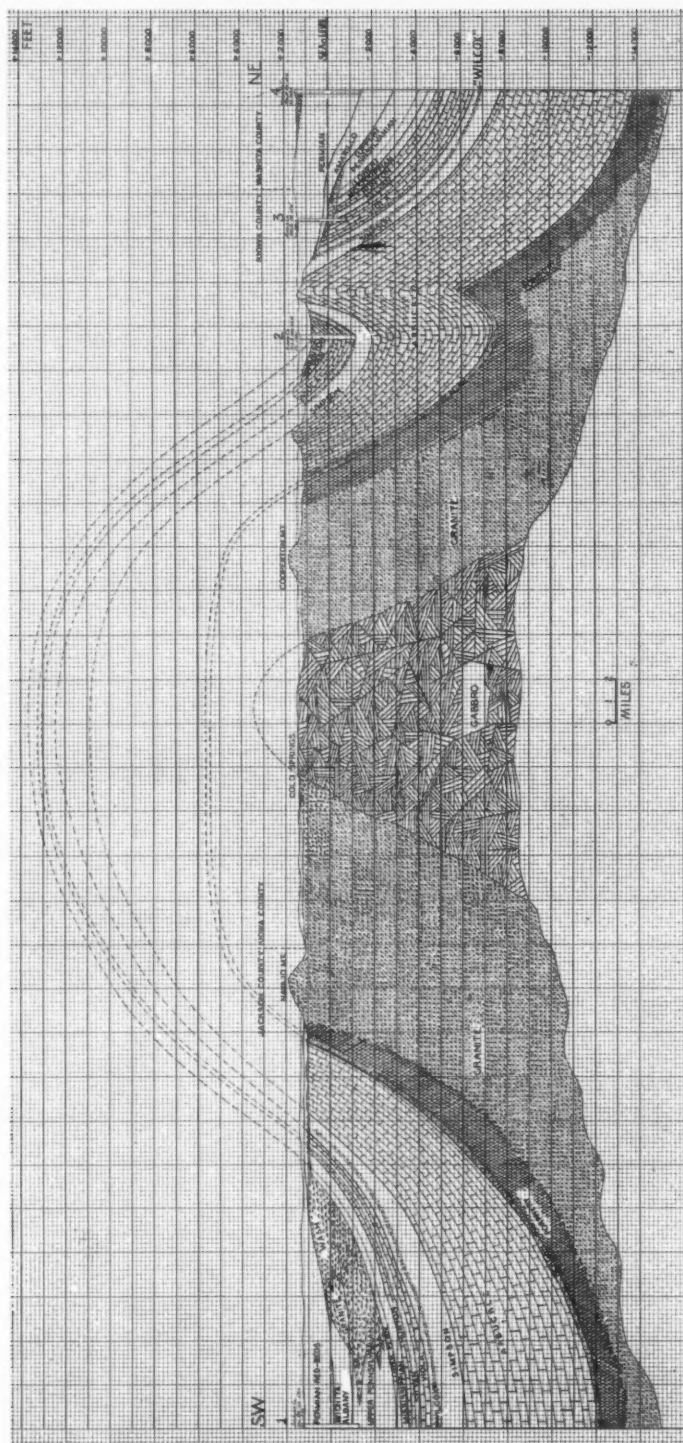


FIG. 2.—Southwest-northeast geologic section through the Wichita uplift. Granite wash shown at southwest end of section is Pennsylvanian (Pontotoc) in age. Geology by Clyde M. Becker and Jack Fulton. 1, Douglas Oil Company's (Central Oil Refining Company's) Marlin No. 1, Sec. 20, T. 1 S., R. 20 W.; 2, Johnston-McDowell's Wedels No. 1, Sec. 6, T. 6 N., R. 15 W.; 3, Hartman-Bucy's (M. C. Ent's) P. Reimer No. 1, Sec. 8, T. 7 N., R. 15 W.; 4, Roxana Petroleum Corporation's (McCoy's) Pretreaters No. 1, Sec. 9, T. 8 N., R. 15 W.

Cold Springs eastward to the west end of the Wichita Forest and Game Preserve, and from Cold Springs westward at least as far as the north fork of Red River on the west line of T. 4 N., R. 18 W., Kiowa County. These intrusions seem to be batholiths. Proofs will be discussed later.

AGE OF WICHITA UPLIFT

J. A. Taff,¹ after a study of the Wichita and Arbuckle uplifts, places the time of the Wichita uplift as ranging from middle to late Pennsylvanian. Since Taff's report, pre-uplift sediments have been identified as of Hunton age, and possibly Mississippian and older Pennsylvanian, in wells drilled in the Gotebo area. The writer's study leads him to believe that Taff's statement of the age of the uplift is correct for the Northeast and Central granite ridges, but there is a possibility that the Southwest ridge is older, because the granite wash which flanks this ridge is thicker, by hundreds of feet, than the eroded material which flanks the other granite ridges. Another condition which indicates that the Southwest ridge is older is the fact that the granites are more faulted than in the Central and Northeast ridges. These faults strike from S. 60° W. to S. 85° W., although faults found in the other ridges strike approximately N. 60° W., and parallel the axis of the uplift.

The faults found in the Southwest ridge have approximately the strike of a surface structural "high" which Hastings Moore has mapped in the vicinity of the town of Alfalfa, T. 9 N., R. 13 W., Caddo County, and which continues northeastward at least as far as T. 14 N., R. 9 W., Canadian County. The writer believes this surface structure outlines a buried ridge which crosses the Anadarko basin where Moore mapped his structure, and as the strike is an indication of a ridge belonging to the Nemaha system, and the strike of the faults in the Southwest ridge is approximately parallel with this structure, they seem to be related, and the age of the Nemaha uplift is believed to be Mississippian. Therefore, if this is correct, the Southwest ridge is pre-Nemaha. This, however, is a problem for further study.

ORIGIN. ACCEPTED THEORIES

Taff² advances the theory that the Wichita Mountains were elevated by folding without the development of vulcanism, that the gabbros are the oldest rocks and were intruded by the granite magmas

¹J. A. Taff, "Preliminary Report on the Geology of the Arbuckle and Wichita Mountains, in Indian Territory and Oklahoma," *U. S. Geol. Survey Prof. Paper* 31 (1904).

²*Op. cit.*

which spread over and submerged the gabbros in the form of a laccolith, that all vulcanism had ceased long before the uplift, and that the present igneous exposures are merely a part of the basement formations and are of pre-Cambrian age. These theories are concurred in by C. H. Taylor.¹ Taff also assumes that the Arbuckle Mountains and the Wichita Mountains represent one continuous uplift.

Later developments have proved that the Arbuckles and the Wichitas are not one continuous ridge, but are separated by a deep syncline, and that instead of the Wichitas being one granite ridge, there are three, as previously stated. The *en echelon* arrangement of these ridges strengthens the theory of folding as expressed by Taff, but other evidence, contradictory to the theory of folding, seems to the writer to be insurmountable.

1. The theory of folding must assume a thrust movement of great magnitude which came from the northeast or southwest. But the writer finds no evidence of such movement from any direction; on the contrary, the minor folds which parallel the axis of the Wichita ridges seem to have been caused by thrusts developed by the uplifting of the mass of the Wichita Mountains.

2. If folding were due to thrusting there should be overturned folds and thrust faults, but the Northeast ridge, which is an anticline with a granite core, seems to have been developed by the uplift of the igneous mass. The axis of the sedimentary strata is directly above the axis of the igneous core, and the Blue Canyon fault, which is parallel with the igneous ridge and immediately southwest of it, is a normal fault. The only evidence of thrust forces is found in the syncline between the Northeast ridge and the Central ridge. This thrusting is a result of compression of the sedimentary strata between two contemporaneous granite uplifts.

3. Had there been any folding, the basic rocks are of such a nature, being largely composed of hornblende, that they would have been reduced to schists, but there is neither schistosity nor orientation of crystals to positions paralleling lines of force.

4. The theory that the granites intruded the gabbros seems inexplicable. In the writer's opinion all the evidence in the field proves that the basic rocks intruded the granites. The arrangement of the gabbro masses surrounded by granite is strong proof that they are intrusive. Furthermore, the granite is tremendously fractured in its zones of contact with the gabbro, but the gabbro is not fractured or even

¹C. H. Taylor, "Granites of Oklahoma," *Oklahoma Geol. Survey Bull.* 20 (1915).

schistose and shows no thermal alteration of any kind. On the contrary, and most conclusive, is the fact that thermal metamorphism, undoubtedly having its source in basic intrusive magmas, is found in the granite along fracture zones several hundred feet from the gabbro contact; also, the granite in some places has been so changed in form by the action of ferro-magnesian minerals expelled by these basic magmas as to have the color of diorite, and where this metamorphism has occurred crystals of magnetite, sphalerite, and galena are found. There are several dikes of basic rock within the granite far from any large basic mass. Perhaps the best defined is southwest of the town of Lugert in Sec. 27, T. 5 N., R. 20 W., Kiowa County.

The writer's theory of the genetic development of the Wichita uplift is as follows. The uplift was caused by the ascension of three great acidic magmas which came up along parallel lines of weakness the positions of which are now shown by the three granite ridges previously described. These magmas rose so slowly that they elevated all the overlying sedimentary strata. Soon after the primary uplift these granitic masses were themselves intruded by the basic magmas which are now represented by the exposures of gabbro previously described. Instead of being a part of the basement complex, the igneous rocks now exposed in the Wichitas are of the same age as the uplift. The Wichita uplift, therefore, was caused by the ascension of three batholiths instead of by folding.

Proofs. Wherever the perimeter of the granite is proved by its contact with the pre-uplift sediments, the magma cooled as a porphyry, but in the interior of the mass a fully developed granite is found, a condition typical of the batholiths.

In the Northeast ridge, where the igneous intrusion is narrow, cooling was rapid, and the entire magma crystallized as a porphyry. Wherever this porphyry came into contact with the Reagan sandstone, thermal action and pressure metamorphosed the sandstone to a highly foliated quartzite, and in the immediate contact, deposits of hematite are found. But where the granite has come into contact with the Arbuckle limestone, because of the throw of the Blue Canyon fault, the limestone shows no thermal metamorphism.

Throughout the mountains the writer has observed several typical veins which occupy faults. One southwest of Hobart, Kiowa County, is well exposed in a mountain in Sec. 7, T. 6 N., R. 18 W., and Sec. 12, T. 6 N., R. 19 W. The fault it occupies seems to cut through the mountains for several miles. Such a fault would be a natural zone of weak-

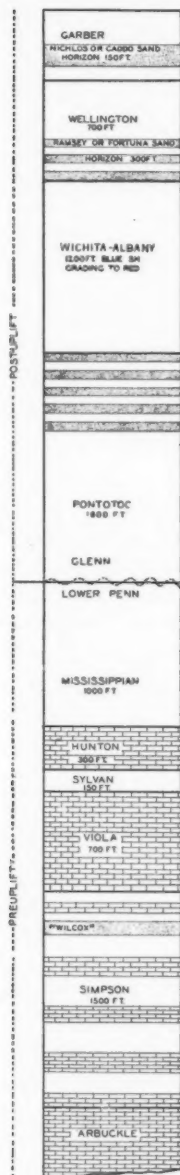
ness, and movement would occur along such a zone if it had been there before the uplift. An assay of samples from the surface-enriched top of this vein showed about 10 per cent copper, and hand-picked samples contained as much as 13 per cent. A shaft was sunk 49 feet deep on the vein, and although the vein material showed some slickensides and gouge, no signs of any extensive movement were observed. This condition seems to be typical of other veins. One mineralized vein in the gabbro west of the west gate of the Forest Reserve is an example of perfect vein structure. The vein is mineralized and some excellent specimens of cuprite and native copper have been found. The vein is not extensively faulted, however, and does not seem to have been much disturbed since formed. Had there been folding since the formation of these veins they would surely be much faulted and disturbed.

MAGNITUDE OF UPLIFT

The Wichita uplift, from the bottom of the Anadarko syncline at Cloud Chief, to the axis of the Palo Duro basin in central Harmon County, is 60 miles in width. A study of both pre-uplift and post-uplift sedimentary formations, with a reasonable allowance for erosion of the granite ridges, indicates that the highest part of the Wichitas was approximately 18,700 feet above the Anadarko syncline and 17,300 feet above the bottom of the Palo Duro basin. This statement is based on the assumption that the granite reached a plus elevation of 5,000 feet as compared to present sea level and was overlain by pre-uplift sediments in ascending order, as follows: Reagan sandstone, 300 feet; Arbuckle limestone, 6,000; Simpson formation, 1,600; Viola limestone, 500; Sylvan shale, 150; Devonian, Hunton limestone, 350; and Mississippian-lower Pennsylvanian, probably 1,000 feet, making a total plus elevation of approximately 14,900 feet, including the granite. It is also assumed that the top of the lower Pennsylvanian in the bottom of the Anadarko basin would approximate minus 3,800 feet and in the Palo Duro basin minus 2,400 feet.

STRATIGRAPHY

As shown in the preceding paragraph, the pre-uplift stratified formations have an approximate thickness of 10,000 feet. The principal interest of the petroleum geologist in these formations is the possibility for the development of oil and gas in horizons known to be productive in other Oklahoma fields. These formations are the upper Arbuckle limestone, known as the "Siliceous lime," the sands of the Simpson



formation, principally the "Wilcox," and the Hunton limestones, as well as possible sands in the lower Pennsylvanian.

The "Wilcox" has been identified in at least two wells. The Marland Oil Company's well in the SW. $\frac{1}{4}$, Sec. 13, T. 7 N., R. 16 W., Kiowa County, had approximately 200 feet of "Wilcox" sand which contained small showings of oil and gas. This identification was concurred in by F. L. Aurin, Glenn C. Clark, and Ira H. Cram. Johnston-McDowell's Wedels No. 1 in the NW. $\frac{1}{4}$, Sec. 6, T. 6 N., R. 15 W., Kiowa County, had drilled 120 feet of the "Wilcox" horizon, when the hole filled with water, and the well was abandoned. Identification of formations was made by Ira H. Cram and Fanny C. Edson. These are the only two wells where positive identification by competent authorities has been made, but several other wells had showings in the pre-uplift formations. J. L. Nation's Huber No. 1, Sec. 22, T. 7 N., R. 16 W., Kiowa County, had a very good showing of high-gravity oil in a formation which seemed to correspond stratigraphically with a sandy phase of the basal Viola. Hartman-Bucy's P. Reimer No. 1, NW. $\frac{1}{4}$, SE. $\frac{1}{4}$, Sec. 8, T. 7 N., R. 14 W., Kiowa County, had a strong showing of heavy oil in what seemed to be the Viola limestone. The Justice Oil Company's Harwell No. 1, NE. $\frac{1}{4}$, Sec. 8, T. 6 N., R. 13 W., Caddo County, had a good showing of gas in the basal Simpson or upper Arbuckle limestone. The Clyde Merryman test, NW. $\frac{1}{4}$, Sec. 7, T. 4 N., R. 11 W., Comanche County, had a showing of oil in a sand in the lower Simpson. The Becker-Reed Oil and Gas Company's Hines No. 1, NE. $\frac{1}{4}$, NE. $\frac{1}{4}$, Sec. 30, T. 4 N., R. 10 W., Comanche County, topped what is believed to be the Hunton at 1,445 feet, and from 1,730 to 1,740 feet in the

FIG. 3.—Stratigraphic section from Garber sandstone to Arbuckle limestone.

basal Hunton had a showing of oil and gas. This test topped the Viola limestone at 2,025 feet and was abandoned, because of a bad hole, at 2,510 feet. Almost all of the Hunton and all of the Viola gave off the odor of petroleum. Ashton-Abernathy's Rose No. 1 in Sec. 32, T. 4 N., R. 10 W., Comanche County, seemed to be a commercial well in the upper Viola from 2,240 to 2,250 feet and pipe was set, but the hole was lost because of an unfortunate fishing job. The Magnolia Petroleum Company's Kerthaus No. 1, SW. $\frac{1}{4}$, SE. $\frac{1}{4}$, Sec. 20, T. 1 N., R. 10 W., Comanche County, reached the top of the "Wilcox" sand, according to the writer's opinion, at 2,235 feet, and went out of the formation at 2,355 feet. The well flowed artesian sulphur water.

The foregoing data are given to prove the presence of the "Wilcox" sand, and other possible producing horizons, and to demonstrate that oil may be expected from these formations if wells are drilled on well-defined closed structures.

POST-UPLIFT SEDIMENTS

The post-uplift sediments are unconformable with, and overlap, the truncated edges of the pre-uplift strata in the immediate area of the Wichita uplift. In ascending order they are: Pennsylvanian¹ (Glenn and Pontotoc, ranging from 1,500 to 2,000 feet thick); Permian (Wichita-Albany, 700-1,200 feet); and Permian Red-beds, from the top of the Wichita-Albany to the top of the Cloud Chief, 2,700-3,000 feet. The Quartermaster formation at the top of the Permian is approximately 300 feet thick.

The Glenn formation in this area consists chiefly of blue and brown shales and thin limestones. The Pontotoc formation, close to the Wichita uplift, is principally granite wash which, farther from the uplift, becomes finer and more decomposed so that it is difficult to differentiate from typical Permian Red-beds. The basal Permian Wichita-Albany formation represents a very distinct change from the Pontotoc and was not deposited until the Wichitas had been so far eroded that they were contributing no more material to the sediments around their base, for the basal Wichita-Albany, instead of being a granite wash, is composed of a series of deep-water anhydrites, limestones, and dolomites, separated by hard blue shale. The upper half of the Wichita-Albany contains a few beds of limestone or anhydrite separated by thick beds of blue or black shale.

¹In the writer's opinion, this upper Pennsylvanian is approximately equivalent to the Canyon and Cisco formations of northern Texas.

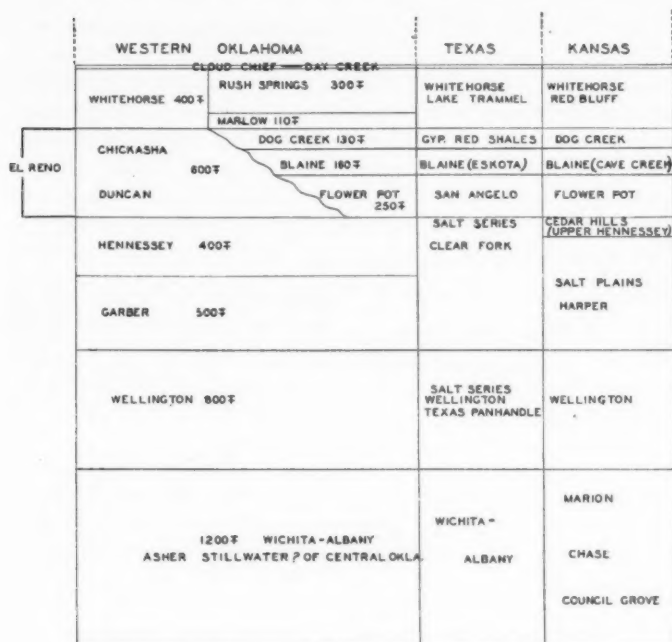


FIG. 4.—Generalized geologic section and correlation of the Permian. Thickness shown in feet.

Water marks developed from long wave action are found in the western Wichita Mountains southwest of Devils Canyon near the Orient Railroad, where the cliffs have been polished by the action of the waves. Also around the east side of the mountain in Sec. 6, T. 5 N., R. 18 W., 8 miles southwest of Hobart, Kiowa County, the Permian Red-beds are now being eroded from granite formations which have been highly polished by wave action. The level of the wave action in both localities is very nearly identical. The writer believes this wave action occurred in the sea which submerged the area at the close of the Pennsylvanian. From this water line down to the top of the Wichita-Albany, the thickness of deposition ranges from 500 to 1,000 feet, indicating the depth of the water in which the Wichita-Albany was laid down.

The Permian Red-beds, which begin at the top of the Wichita-Albany formation, represent another very distinct lithologic change,

being composed entirely of clastic sediments deposited in shallow water. The lithology of the Red-beds is so well known that it is unnecessary to discuss it. The general divisions in ascending order are: Wellington shale, 700-800 feet; Garber sandstone, 200-300 feet; Hennessy shale, 600-700 feet; Chickasha-Duncan sandstone, which by lateral gradation becomes the Flower Pot, Blaine, and Dog Creek, in ascending order, 575-650 feet; Marlow¹ basal Whitehorse, 110-135 feet; Rush Springs¹ upper Whitehorse, 250-300 feet; Cloud Chief gypsum, 10-130 feet.

OIL HORIZONS OF POST-UPLIFT FORMATIONS

Duncan district.—Fields in the Duncan district producing oil or gas from post-uplift formations are: Comanche, South Empire, North Empire, or Gas City, Kilgore, Parsons-Gant, Walters, Hanberry, and possibly the Lawton shallow field. Oil and gas are produced from the upper Pennsylvanian, except at Kilgore where the producing formations are basal Wellington and upper Wichita-Albany.

Grady-Caddo county fields.—Carter-Knox, Harness, the Chickasha gas field, and the Cement oil and gas field produce oil or gas from post-uplift formations. The principal production is from the basal Wellington, called the Ramsey horizon in the Chickasha gas field, Knox sand in Carter-Knox, and the Fortuna sand at Cement. Shallow gas is produced from the Garber sand, called Caddo sand at Cement, and Nichlos sand in the Chickasha gas field. In the Carter-Knox field commercial oil is found in the Wichita-Albany and upper Pennsylvanian. The Chickasha gas field is producing probably from the basal Wichita-Albany in one well, the Magnolia Petroleum Company's Irvin No. 1, Sec. 14, T. 5 N., R. 8 W., Grady County.²

Sayre oil and gas field, Beckham County.—The principal production of the Sayre field is from the basal Wichita-Albany and upper Pennsylvanian. From the foregoing data it is seen that there are four general horizons of production, as follows: upper Pennsylvanian, basal Permian (Wichita-Albany), basal Red-beds (Wellington), and the Garber sandstone.

DEPTH TO "WILCOX" SAND

The thickness of the section from the Nichlos sand (Garber) to the 2,600-foot, or deepest producing sand in the Duncan district, is approx-

¹The names, Marlow and Rush Springs, are suggested by Roger W. Sawyer and Frank C. Greene.

²Sands in the lower Wichita-Albany are now being developed in the Cement field, the production ranging from 150 to 800 barrels per day.

imately 2,500 feet. From the top of this deep sand at Duncan to the top of what the writer believes to be the Viola limestone in the Amerada Petroleum Corporation's Blades No. 11 in the NE. $\frac{1}{4}$, NE. $\frac{1}{4}$, Sec. 32, T. 1 S., R. 8 W., Stephens County, is 770 feet. The Viola ranges from 500 to 800 feet in thickness in the Wichita area. It is 200 feet from the base of the Viola to the top of the "Wilcox" at Gotebo. These figures show, theoretically, that the depth from the basal Garber to the "Wilcox" in the Duncan field is 4,270 feet, the basal Garber being the Nichlos sand previously mentioned. On this basis the depth to the "Wilcox" in the following fields would be as follows: Cement, 6,000-6,200 feet; Chickasha gas area, 5,800-6,000; Carter-Knox, 5,500-5,800; and Harness gas field, 5,700-5,900 feet. But, in computing the depth to the "Wilcox" it must be remembered that all the pre-uplift strata have been eroded down to the top of the Viola in the Duncan field, and these figures have been based on the assumption that the same amount of erosion has taken place on the structural "high" upon which these fields are located, and as some of the structures may not have been eroded at all, and others only partly eroded to the Viola, it is seen that there is a variable factor in the amount of erosion which must be added to the estimated depths to the "Wilcox" in the several fields, which will range from almost nothing to possibly 1,500 feet.

PROSPECTIVE AREAS FOR OIL AND GAS DEVELOPMENT

Inasmuch as all production to date has come from structures of mountain-folding type either directly related to the axis of the Wichita ridges, or to the Arbuckle uplift, or to folds resulting from forces caused by the diastrophism of the period of uplift, a study of these structures is necessary to the successful prediction of new fields. Future production is expected to be found on extensions of the known producing folds and others which are in alignment with these structures.

It is further to be expected that production will be found on the general "high" referred to as being parallel with the folding of Nemaha time, and as crossing the Anadarko syncline at Alfalfa, Caddo County, and traversing Caddo, Canadian, Blaine, and Kingfisher counties in the general direction of the strike of the Nemaha granite ridge, and in the same general direction as the strike of the faults in the Southwest ridge of the Wichitas.

A third area of probable production is along a series of structural "highs" in eastern Grady and western McClain counties. The surface beds of this area are extremely difficult to detail, but there is undoubted

folding which parallels in a general way the Grady County anticline which lies on the southwest, and the Oklahoma City structure which lies on the northeast.

On folds directly related to the Wichita uplift, the area of Jefferson County warrants careful detailed study, as do southern Washita County and the north tier of townships of Kiowa County. Southern Beckham and northern Greer counties are also important areas for possible oil and gas production.

PERMIAN RED-BEDS—LATERAL GRADATIONS

The writer's study of the Permian Red-beds convinces him that all of the clastic material from the top of the Wichita-Albany or base of the Wellington to the base of the Whitehorse sandstone came from the southeast, probably from the Ouachita uplift, because all the formations grade from sand or sandy shale to impalpably fine clays and shales, from the area between the base of the Arbuckles and Cimarron River extending westward into Caddo, Canadian, Blaine, and western Oklahoma counties; that is, in a line beginning at the Arbuckles and extending north to Cimarron River all the formations are very sandy, but logs of wells drilled west of this line show a lower and lower percentage of sand toward the west, until almost no sand is found in the Red-beds in wells drilled in Canadian, Blaine, northern Caddo, and counties farther west.

The basal part of the Whitehorse sandstone may have had the same origin, but there is some doubt about this, for the sandstone in this formation, which Sawyer has named the Marlow, continues uninterruptedly far out into the basin; in fact, becomes more sandy in the general area where the sands disappear from the lower strata. The Marlow was probably derived from wind-blown sand deposited in shallow water, and represents the southwest limit of an old sea.

The upper Whitehorse, or Rush Springs, seems to be nearly all wind-blown sand, although local clay and gypsum deposits indicate the presence of shallow ponds and small lakes within the area of the Permian desert.

The Cloud Chief gypsum and Day Creek dolomite above the Whitehorse sandstone represent the retreating period of a sea which for a short time flooded the Whitehorse desert. Evidently the gypsum and dolomite were precipitated from this sea upon a low topography. The writer has found hills of Whitehorse sandstone protruding through the Cloud Chief gypsum, and assumes that these inliers were islands during the period of precipitation. Because of these facts the writer believes that much of

the structure detailed on the Cloud Chief represents only Whitehorse topography, and that the only value in mapping this formation is to determine general regional conditions or to outline very large structures where the closure is so pronounced as to be indisputable.

CHICKASHA-DUNCAN FORMATION

Below the base of the Whitehorse is 600 feet of section which has been a matter of geological controversy for years. In the summer of 1922, Roger W. Sawyer detailed the top of the Chickasha formation from a point 15 miles east of the Marlow, Stephens County, around the north side of the Wichita Mountains to Apache, T. 5 N., R. 11 W., Caddo County; then from the point east of the Marlow he worked northward around the east end of the Anadarko syncline to a point 7 miles west of El Reno, Canadian County. After doing this work he stated¹ that the lower 100-120 feet of the Whitehorse should be given the name of Marlow, and treated as a separate formation, and he contended that the Chickasha-Duncan sandstone, which constitutes the 600 feet of section below the base of the Marlow and the top of the Hennessey shale, changes through lateral gradation to the Dog Creek, Blaine, and upper Enid formations. Geologists of the Becker-Reed Oil and Gas Company have detailed all the area covered by Sawyer and have extended their work considerably beyond the territory he discussed, and they agree that his conclusions are correct and that the Chickasha-Duncan positively grades into the Dog Creek, Blaine, and Flower Pot of the upper Enid. They go farther, and state that the base of the Duncan corresponds with the base of the Flower Pot. They also find that the base of the Duncan extending around the west end of the Wichitas is 250-270 feet below the base of the Blaine, and that this interval corresponds very closely with the interval in Texas between the base of the Blaine and the Merkle dolomite at the base of the San Angelo formation. Therefore, the base of the Flower Pot, and the base of the Duncan, and the base of the San Angelo are one continuous formation, and the top of the Hennessey of Oklahoma, which underlies the Duncan and Flower Pot, corresponds with the top of the Clear Fork of Texas (Fig. 6). This shows the relationship of the base of the 600 feet of section below the base of the Whitehorse, or Marlow. The proof of the relationship of the upper part of this section is shown in an exposure in Sec. 4, T. 5 N., R. 7 W., Grady County, south of Little Washita River, where the top of the Chickasha is in contact with

¹Roger W. Sawyer, "Areal Geology of a Part of Southwestern Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8 (1924), pp. 312-21.

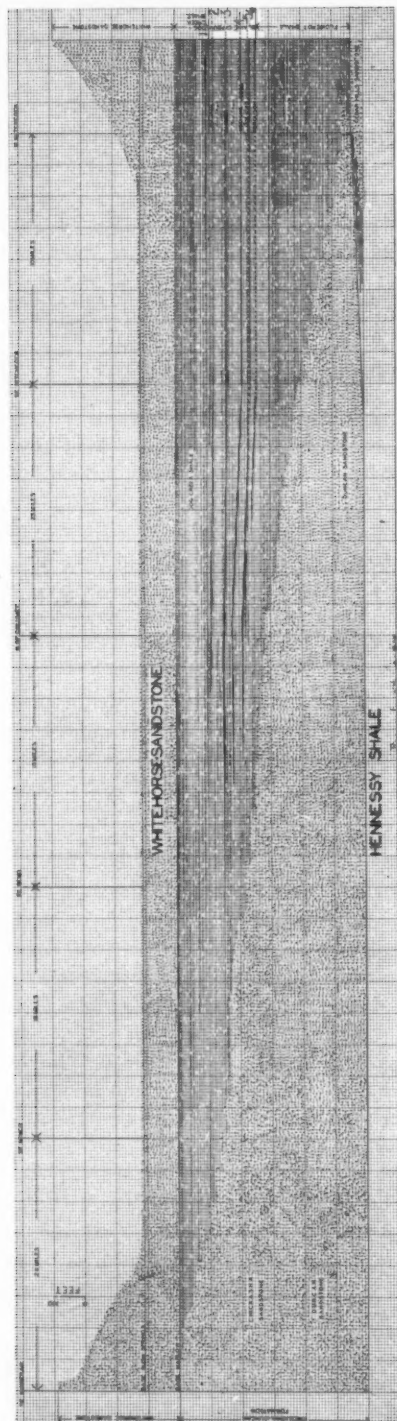


FIG. 5.—Ideal southeast-northwest geologic section showing transition of Chickasha-Duncan formation to Dog Creek shale, Blaine gypsum, and Flower Pot shale, from area southeast of Ninnekah, T. 5 N., R. 7 W., Grady County, to area north of Hitchcock, T. 17 N., R. 11 W., Blaine County. Legend: 1, Dolomite; 2, Dolomite; 3, Dolomite A; 4, Dolomite B; 5, "Gyp," B; 6, dirty white "gyp." Geology of Figures 5, 6, and 8 by Becker-Reed Oil Company staff; geologists, Clyde M. Becker, Walde-mar Ervin, Jack Fulton, Allan B. Gray, P. A. Wallace, Murray Wells; instrument men, Fred Brasted, Jr., Fred A. Devin, Roy Cooper.

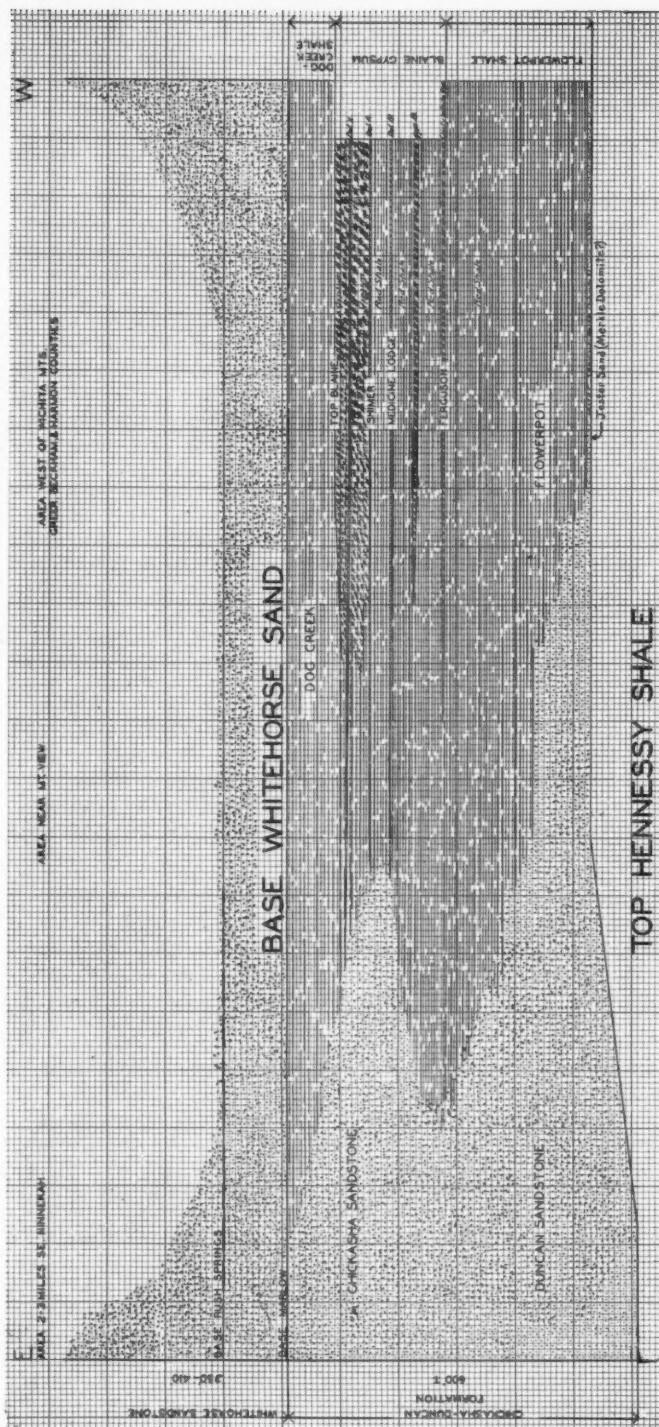


FIG. 6.—Ideal east-west geologic section from area southeast of Ninnekah, T. 5 N., R. 7 W., Grady County, to Greer, Beckham, and Harmon counties through north flank of Wichita Mountains, showing transition of Chickasha-Duncan formation to Dog Creek shale, Blaine gypsum, and Flower Pot shale. Thicknesses shown in feet.

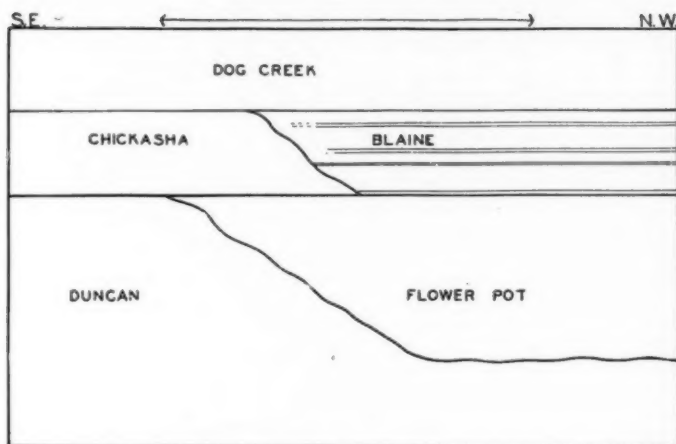


FIG. 7.—Transition of Chickasha-Duncan to Blaine and Flower Pot formations near Mountain View, Caddo-Kiowa county line.

the base of the Whitehorse. Toward the northwest the base of the Whitehorse can be detailed, almost without a break in the outcrop, to the bluffs northwest of Greenfield in Sec. 19, T. 15 N., R. 11 W., Blaine County. There it rests upon 130 feet of Dog Creek shale. The top of the Blaine is found at Greenfield. The thickness of the Blaine section northeast of Greenfield, in T. 16 N., R. 10 W., is 160 feet. In the same township there is 200 feet of Flower Pot below the Blaine, and below the Flower Pot is approximately 75-100 feet of typical Duncan sandstone. This Duncan sandstone feathers out into the Flower Pot approximately 12 miles north in T. 17-18 N., R. 10 W. Thus it may be seen that from the base of the Whitehorse at Greenfield, down through the Dog Creek, Blaine, Flower Pot, and remaining Duncan, the thickness of the section is approximately 600 feet to the top of the Hennessey shale which underlies the Duncan. This is the thickness of the Chickasha-Duncan, as shown by well logs in the area of the Chickasha gas field and in all the territory where the top of the Chickasha is in contact with the base of the Whitehorse.

Starting again from the point south of Little Washita River in Sec. 4, T. 5 N., R. 7 W., Grady County, and going westward through the Chickasha and Cement oil fields, then finding the base of the Whitehorse outcrop west of the Cement oil field, and following this outcrop north-

west to Mountain View, Kiowa County, one finds that the Chickasha has changed to 90-100 feet of Dog Creek, 100-120 feet of Blaine, 200-220 feet of Flower Pot, and approximately 100 feet of Duncan sandstone which is well exposed northwest of Gotebo in T. 7 N., R. 17 W. Here, also, the interval is approximately 600 feet to the base of the Duncan from the base of the Whitehorse. By following the base of the Duncan westward, to the west end of the Wichita Mountains west of Granite, and mapping this contact farther west, to the region of Haystack Mountain, T. 8 N., R. 23 W., Beckham County, where the Duncan feathers out into the Flower Pot, one again finds that the interval from the base of the Duncan up through the Flower Pot, Blaine, and Dog Creek to the base of the Whitehorse, where it is exposed in Sec. 29, T. 7 N., R. 24 W., Greer County, is approximately 600 feet.

For a study of the gradation of the Chickasha into the Blaine, there are two important areas: (1) the area from Sec. 24, T. 7 N., R. 15 W., where the fossiliferous dolomite bed of the Blaine is in contact with the typical Chickasha sandstone, northwestward 7 miles to the area west of Mountain View, where all the Chickasha has disappeared and four beds of the Blaine have been developed; (2) the area beginning northwest of El Reno and continuing northward to the area northeast of North Canadian River, a distance of approximately 10 miles. In this distance the whole Blaine series is developed from sediments of Chickasha age.

At a conference of the geologists who had detailed the areas here described the stratigraphy was discussed and it was decided to suggest the name El Reno formation to include the 600 feet of section from the top of the Hennessey to the base of the Whitehorse. The following geologists attended this conference: Bartell and Buck, of the Skelly Oil Company; Buckstaff and Schweer of the Shell Petroleum Corporation; Potter and Clifford, of the Indian Territory Illuminating Oil Company; Brown, of the Gypsy Oil Company; and Fulton, Wells, and Becker, of the Becker-Reed Oil and Gas Company.

TRANSITION IN LITHOLOGY OF LOWER PERMIAN

WICHITA-ALBANY FORMATION

Below the Duncan sandstone are the Hennessey, Garber, and Wellington formations. The base of the Wellington is the base of the Permian Red-beds. Below the Wellington there is a section, ranging from 900 to 1,200 feet in thickness, of non-red Permian known in Texas as the Wichita-Albany, which may be closely correlated with the Asher-Stillwater of central Oklahoma, and the Marion, Chase, and Council

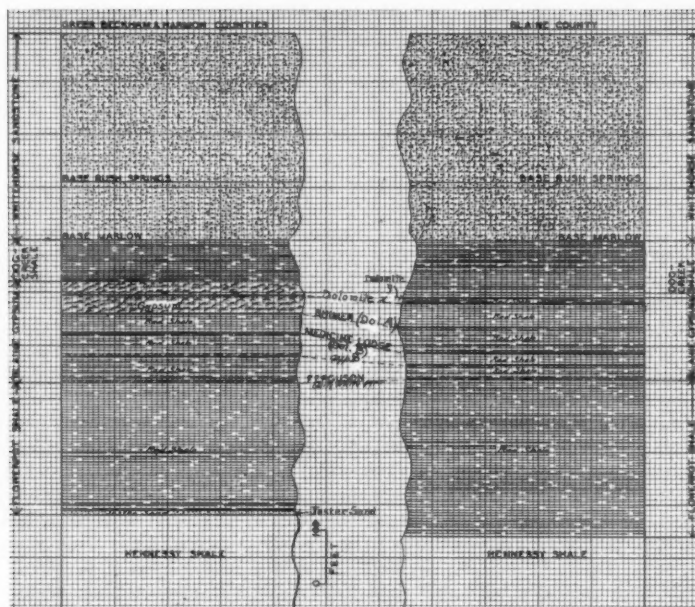


FIG. 8.—Ideal cross sections of Blaine formation west of the Wichita Mountains and Blaine formation of Blaine County, Oklahoma.

Grove of Kansas. A study of this formation in southwestern Oklahoma, from data obtained from well logs, shows that it grades from a series of soft blue and brown shale and thin sandy limestones and sandstones, in the area from the northwestern point of the Arbuckle Mountains, northwestward through the Robberson, Carter-Knox, Chickasha, and Cement oil fields, into a series of hard, well-developed blue shales, limestones, dolomites, and anhydrites in the area extending from the Wichita Mountains to the western part of the state. Evidently, therefore, the material of the Wichita-Albany formation, like that of the Red-beds, was derived from some source on the southeast, probably the Arbuckle and Ouachita uplifts.

The evidence of the lithology of the lower Permian, adjacent to the Wichitas, shows that these mountains contributed nothing to the sediments of that time. And, inasmuch as the latest Pennsylvanian or Pontotoc sediments around the base of the Wichitas consist chiefly of granite wash, this material must represent the final stage of the erosion of the Wichita uplift.

AGE OF THE OUACHITA OROGENY AND ITS TECTONIC EFFECTS¹

FRANK A. MELTON²
Norman, Oklahoma

ABSTRACT

Evidences which have been previously advanced relative to the age of the Ouachita orogeny are reviewed and discussed in the first part of the paper. The conclusion is drawn that there is very little evidence in support of a Pennsylvanian age that will withstand a close examination. The chief evidence cited is the presence of chert-pebble conglomerates in the lower Pennsylvanian formations of the eastern part of the Lehigh syncline and northward. The supposition that these chert pebbles originated in the Talihina "chert" formation of Black Knob Ridge (which borders the syncline on the east) is shown to be probably incorrect. In view of the evidence presented, the buried southeastern extension of the Arbuckle Mountains is thought to be a more probable source.

Additional evidence relative to the age of the exposed Ouachita Mountains is found in the joint systems of the central and northern Oklahoma plains. This evidence leaves no doubt whatever that an important part of the more intense phases of the Ouachita orogeny occurred after early (Oklahoma) Permian time, and there seems to be a strong probability that all of it occurred then. One of the chief joint systems of central Oklahoma radiates fan-like from the front of the Ouachita Mountain arc, and apparently decreases in "intensity" with distance from these mountains. The short faults of the so-called "*en echelon* fault belts" in central Oklahoma may be correlated very closely in strike with the joints of the radiating system referred to, and are thus, from the standpoint of origin, connected with these mountains more closely than before. Doubts are expressed as to the common occurrence of true *en echelon* fault belts in Oklahoma.

REVIEW OF PREVIOUS CONTRIBUTIONS

The time at which the visible Ouachita Mountains were formed has been placed by different investigators in different parts of the Pennsylvanian period, ranging from early (Atoka) and middle (Seminole) to late Pennsylvanian. Others have contended that the mountains were formed in late or post-Permian time. There has been very little discussion of age, but these contradictory conclusions are found in the literature about the region. Taff, McCoy, and Miser, several years ago, and more recently Clawson, Powers, and Cheney, have all contributed to this literature, and all agree in placing the orogeny somewhere in the Pennsylvanian period. Taff³ (2, p. 5), though not stating the age of the

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deformation explicitly, implied that it took place in early Pennsylvanian time. McCoy (4, p. 562), on the basis of evidence to be cited later, also concluded that the "north Ouachita" movement occurred in the early part of the Pennsylvanian period, near the end of the time during which the Boggy formation was deposited. Miser (3, p. 64 and p. 82) believed that the beds of the Ouachita geosyncline "were compressed. . . . late in the Pennsylvanian epoch." Two years later, however, Purdue and Miser (5, p. 9) stated that

in the Ouachita Mountain and Arkansas Valley regions the uplift, folding, and faulting were probably contemporaneous with extensive movements of a like nature in the Arbuckle Mountains, in southern Oklahoma, which took place, according to Moore, near the middle of the Pennsylvanian epoch.

In 1928, however, Miser (9, p. 180) again stated that the "deformation took place presumably in late Pennsylvanian time." Clawson (10, pp. 14-15) introduced several lines of structural evidence from the "open fold zone" skirting the Ouachita Mountain front, which prove, in his opinion, the early Pennsylvanian (middle Boggy) age of these folds. Powers (11, pp. 1047-49) introduced the conception of a "pre-Ouachita" diastrophic movement based on the evidence of the boulders in the Caney shale, but followed Taff and McCoy in admitting the evidence for diastrophic movement in Atoka time, and again immediately after the Boggy shale was deposited—both in the early part of the Pennsylvanian period. However, he states "The overthrusting of the Ouachita Mountains to their present position can be assigned to Seminole time" (middle Pennsylvanian). Cheney (12, p. 572) follows the evidence adduced by earlier writers and concludes that "the main folding and initial uplifting of the Ouachita basin region occurred during this. . . . period"—the time represented by the formations from Hartshorne to Boggy inclusive (early Pennsylvanian). Others have drawn similar conclusions. A few, particularly Keith (8), have persisted in considering at least an important part of the Ouachita diastrophic movement as of late or post-Permian age.

The more important evidences cited in favor of an early and middle Pennsylvanian origin are as follows.

1. The thin chert conglomerates found here and there in the lower Pennsylvanian Atoka, Hartshorne, McAlester, Savanna, and Boggy formations along the eastern side of the Lehigh syncline, were, in the opinion of Taff (2, p. 5), derived from Black Knob Ridge, which is composed of the flint and chert of the Talihina "chert" formation. On the geologic map of Oklahoma and in the Atoka Folio, the rocks of the Black

Knob Ridge are shown, just east of the town of Atoka. The ridge extends slightly east of north from the vicinity of Atoka, a distance of 8 miles to Stringtown. According to Taff, these chert conglomerates are thickest, coarsest, and altogether most obvious in the eastern side of the Lehigh syncline adjacent to Black Knob Ridge. They extend several miles along the strike of these formations. The lowest Pennsylvanian formation in contact with this ridge is the Atoka formation, which has a thickness of approximately 3,000 feet. The chert conglomerates in this formation, measured along the strike, are almost equal in extent to the "chert" of Black Knob Ridge. If the source of these conglomerates was the chert and flint of the Talihina formation, the Ouachita Mountains were obviously formed during, or before, early Pennsylvanian time, as the ridge is clearly part of the Ouachita mountain system.

2. The 50-foot white chert conglomerate "mixed with coarse quartz sand" at the base of the Thurman "sandstone" constitutes a marked contrast to the shales and fine sands of the Boggy formation on which it rests. The Thurman sandstone is the lowest of the formations indicated in the symbol marked "Cst" on the *Geologic Map of Oklahoma*.¹ This relationship was thought to indicate a marked orogenic episode in the near-by Ouachita Mountains just prior to the deposition of the conglomerate. The existence of other scattered pebbly chert conglomerates in sandstone formations even higher in the Pennsylvanian section of central Oklahoma has also been thought by some to indicate the contemporaneous existence of the Ouachitas.

3. The apparent sudden termination of the McAlester and Savanna anticlines of the "open-fold zone" near the middle of the Boggy shale was thought by Clawson (10, p. 14) to show that these folds were formed in middle Boggy time.

4. Various obscure evidences for the existence of angular unconformities below and above the Savanna sandstone as well as at the base of the Thurman sandstone were further indications, in the opinion of Clawson (10, pp. 14-15), that the Ouachita orogeny occurred at about this time in the Pennsylvanian period.

5. The curving outcrop of the Thurman sandstone and other superjacent formations northeast of the Arbuckle Mountains and northwest of the westernmost part of the Ouachita Mountains is cited by McCoy (4, p. 562) as "evidence for the north Ouachita movement" with the implication that it was earlier than the Arbuckle Mountain orogeny.

¹U. S. Geol. Survey in cooperation with geologists and oil companies of Oklahoma, and the Oklahoma Geol. Survey (1926).

6. The relatively small amount of chert conglomerates in the Stanley and Jackfork formations (late Mississippian and possibly earliest Pennsylvanian) of the Ouachita Mountains has been cited as evidence that the "old land" of Llanoria could not have been the source of the chert pebbles in the early Pennsylvanian formations bordering the Ouachita Mountains on the northwest (Atoka to Thurman, inclusive (12, p. 572). If this assumption is correct, considerable weight is thus added to the view that the chert pebbles came from exposures of the Talihina "chert" within the exposed Ouachita Mountains; and this in turn would imply that the mountains were in existence in early Pennsylvanian time, much as they are to-day.

7. The Ahlosa fault just south of Ada, at the north end of the Arbuckles, is probably of middle Pennsylvanian age, as it cuts all formations to the top of the Wewoka, and higher strata are only flexed. Because this fault is approximately parallel with the Ouachita overthrusts, Morgan (7, p. 146) was led to believe that it was part of the Ouachita orogeny.

DISCUSSION OF EVIDENCE

It is hardly necessary to make additional field examinations to prove that the chert pebbles in the early Pennsylvanian formations just west of Black Knob Ridge did not have their source in the chert and flint beds of the ridge, since the structural map in the Atoka Folio shows the Talihina "chert" and the Pennsylvanian strata to be separated by a large fault. The Talihina chert beds are standing on edge and may in places be overturned, while the strata of the Atoka formation dip 60° or more toward the Lehigh syncline. All must admit that Black Knob Ridge as it now stands is not the edge of the depositional basin in which the shales, sandstones, and local chert conglomerates of the Atoka formation were deposited.

Is it not possible, some may ask, that the chert beds of the ridge were the source of the chert pebbles in question at an early stage in the orogenic development of the Ouachita Mountains, and that a later recrudescence of movement along this large fault brought these formations to their present close areal position? A rapid reconnaissance of the field relations in this region was made by the writer in June, 1929, and certain evidences obtained which appear to answer this question in the negative.

Three miles southeast of the south end of Black Knob Ridge, in the basal conglomerate of the Trinity sandstone of Lower Cretaceous age occur many pebbles and cobbles of chert and flint ranging in diameter from 0.1 inch to 5 inches. Pebbles of vein quartz and quartzite are also

very common and are ordinarily well rounded. They were doubtless transported a long distance before deposition. The chert and flint pebbles, however, are very angular. A few small pebbles show considerable rounding, but the great majority do not. This angularity is especially noticeable in the smallest and largest of the pebbles. These chert and flint pebbles were transported not less than 3 miles before deposition, and being in the basal conglomerate of the Trinity sandstone they were probably carried by streams flowing into the Lower Cretaceous sea.

This conglomerate is in sharp contrast to the chert conglomerate in a prominent sandstone member of the Atoka formation $\frac{1}{4}$ mile west of the Talihina "chert" outcrop in Black Knob Ridge at Stringtown, Oklahoma. Here the modal diameter of pebbles is probably less than 0.5 inch, although the maximum diameter is about 2 inches. Many pebbles with diameters greater than 1 inch were found and almost without exception they were well rounded. The degree of rounding, however, decreases with the size. The smallest flakes are angular, only the sharp edges having been dulled. It is believed that these pebbles were transported to their resting place by streams, inasmuch as plant remains are found in the same layer. The method of transportation was doubtless similar to that in Lower Cretaceous time already referred to, yet the degree of rounding of the larger pebbles is strikingly different. The great difference in maximum diameters between the pebbles of these two formations is also of considerable significance.

At a place 7 miles southeast of the south end of Black Knob Ridge, a prominent chert and flint conglomerate layer in the Trinity formation rests against a monadnock of Carboniferous sandstone. More than 90 per cent of the pebbles are chert and flint. The modal diameter is between 0.2 and 0.5 inch, though the size range is from less than 0.1 inch to 1 inch. Almost 99 per cent of the pebbles show a strong angularity; only the sharpest edges have been rounded. Not even the larger pebbles have been well rounded, though they were transported not less than 7 miles before deposition. Again the contrast with the chert conglomerate in the Atoka formation, which is only $\frac{1}{4}$ mile from the supposed source of supply, is very marked. This contrast in the degree of rounding of chert and flint pebbles tends to show that the pebbles in the Atoka formation must have been transported more than 7 miles before deposition. The distance was probably considerably greater.

In point of color, too, there is a noticeable difference in the appearance of the Atoka chert conglomerates and those of the Trinity forma-

tion. The Talihina "chert" in the unweathered condition is found in various shades of translucent dark gray, as shown in the large quarry at Stringtown. Weathering, however, has changed it to many shades of light gray, tan, pinkish-tan, and white. In a small gully 100 yards below a weathered hillside of Talihina "chert," the white chert pebbles were found to compose about one-fourth of the total. This is very noticeably less than the percentage of white chert pebbles in conglomerates of the Atoka formation in general, and more than the percentage of white chert pebbles in the conglomerates of the Trinity sandstone southeast of Black Knob Ridge.

It is worth noting that in the Atoka and Colgate folios the word "chert" is almost invariably used in describing the pebbly conglomerates of the early Pennsylvanian formations. This implies that they are generally white, an implication which agrees with the writer's limited field observations.

The degree of whiteness of the weathered chert beds of this region depends to some extent on the length of time they are exposed to weathering, though doubtless there are other factors. In so far as time alone is a factor, the color relations referred to indicate a quick removal and rapid transportation of the slightly weathered surface rocks in Trinity time, and a much slower removal of the weathered surface rocks while the beds of the Atoka formation were being deposited, allowing a much longer time for weathering. This implies that the surface slope was more gentle in Atoka time than during the early part of the Lower Cretaceous period at this place, and this again indicates that the source of the pebbles was farther from their final resting place in the former than in the latter period.

The fact that the exposed conglomerates of the Atoka formation are practically co-extensive with the "chert" of Black Knob Ridge was thought by Taff to be very significant. He believed it to be evident that the "cherts" of the ridge contributed to the chert pebbles of the early Pennsylvanian conglomerates. The writer, however, is not convinced that these relations have the significance thus assigned to them, because it so happens that the "chert" of Black Knob Ridge is concealed by the overlapping Trinity sandstone within less than 1 mile (measured north and south) of the southernmost exposure of the conglomerate-bearing Atoka beds; also those strata of the Atoka formation which have not been removed by erosion south of this point are concealed beneath the Trinity. There is no question that the conglomerates thin westward along the south side of the Lehigh syncline, but it is believed

that the correspondence of the southernmost exposure of Atoka conglomerates with the south end of the "chert" ridge does not in this case imply a causal relation between the two.

Taff has pointed out that the pebbles of the chert conglomerates in these early Pennsylvanian rocks came from the east or southeast. They pinch out toward the west, as do many of the sandstone members of these formations. The Thurman sandstone also was shown to thin from about 250 feet near the sharp change in its strike, to about 80 feet, 25 miles farther west. This thinning is accompanied by a gradual diminution in size of the sand grains as well as a practical disappearance of the chert conglomerate layer.¹

THE BURIED SOUTHEASTERN ARBUCKLE MOUNTAINS—A SOURCE

Notwithstanding the conclusions drawn from these bits of evidence in the past, the writer believes that, together with certain other facts, they point to the buried southeastward extension of the Arbuckle Mountains as the probable source of these Pennsylvanian chert pebbles. The evidences cited by Morgan (6 and 7) show definitely that this end of the Arbuckle Mountains was in existence in McAlester, Savanna, Boggy, Thurman, and later time, and possibly also as early as Hartshorne time. The conglomerates of the Atoka formation extend the time of earliest known Arbuckle folding backward still farther, in the opinion of the writer. B. F. Wallis, in 1915, found a limestone conglomerate at the top of the Wapanucka limestone only a few miles from the easternmost exposure of the Arbuckle Mountains. The fragments looked very much like pieces of the Viola and Arbuckle limestones. These are significant, according to Morgan (7, p. 70), if they are contrasted to the pebbles of the lowest coarse conglomerates of the Pennsylvanian strata farther west in the Arbuckle Mountains, near the town of Franks. Here the fragments are chiefly from the Caney and Woodford formations, which are much higher in the geologic section than the Ordovician Viola and Arbuckle limestones. "The natural conclusion, therefore, is that the Arbuckle Mountains were first uplifted at some point to the south of their present highest position" (7).

The coarse limestone and flint conglomerate near Stapp, in eastern Oklahoma, which Powers (11, p. 1041) refers to the lower part of the Atoka formation, seems to be further evidence of the early Arbuckle

¹This westward thinning of coarse beds is not in conflict with the facts shown by Morgan (7) relative to the increasing coarseness toward the west of some of these same formations, as Morgan's work was done considerably farther west in the Arbuckle Mountains.

orogeny. The largest boulders are 1 foot in diameter and are said to be of Ordovician age.

If it is true that the southeastern extension of the Arbuckle Mountains began to fold as early as Atoka time, it must be admitted that the mountains were in existence at the proper time, and that they had the proper position, to constitute the source of the pebbles in question. This buried extension of the mountains is sufficiently far from the present position of the conglomerates to explain the well rounded nature of the larger pebbles. Judging from the *Geologic Map of Oklahoma*,¹ the Woodford chert, striking southeastward, may be seen directly beneath the overlapping edge of the Trinity sandstone within 3 miles of the easternmost exposure of the Arbuckle Mountain structures. Although the writer has seen some suggestion that parts of the Woodford chert of the Arbuckles weather to a uniform white color more rapidly than the Talihina "chert" of Black Knob Ridge, he has no present intention of stating definitely that this is true. If it is, it helps further to explain the greater percentage of white weathered chert pebbles in the Atoka formation than in the Trinity sandstone. It would, in this regard, constitute an added bit of admissible evidence that the Talihina "chert" of Black Knob Ridge was *at no time in its history* a source of the pebbles which were deposited in the Atoka formation.

The fact that the conglomerates disappear and the sandstones thin westward in these formations, from Atoka to Thurman inclusive, does not prove that a large buried southeastward extension of the Arbuckle Mountains does not exist. The fact could well be explained if the eastern Arbuckles were higher, and therefore undergoing more rapid erosion, than the western part at that time; and the assumption that this was true is in no way unreasonable, if available evidence is considered.

The lack of pebbles and boulders of sandstone and quartzitic sandstone from the underlying formations, in the Thurman conglomerate, and the lack of other evidence that the base of this formation constitutes a major unconformity, or even a major change in depositional history, point toward relatively mild changes at the end of Boggy time rather than the huge orogenic disturbance that marked the formation of the Ouachita Mountains.

The apparently sudden termination of the McAlester and Savanna anticlines of the open-fold zone, near the middle of the Boggy shale, does not prove that the folds were formed in middle Boggy time. A prominent unconformity and important changes in deposition should be in

¹U. S. Geol. Survey *et al.*

evidence if this were a fact. The thick Boggy shale (2,000-2,600 feet) may well have acted as an effective "shock absorber," dissipating some of the forces arising from the Ouachita compression, thus protecting some of the more rigid overlying formations from folding.

In eastern Oklahoma on the northern side of the Ouachita Mountains, the open-fold zone extends farther north than at the west end under consideration on the preceeding page. As many have pointed out, the lower part of the sedimentary section was deformed more than the higher part during the orogenic episodes of this region; and this is perhaps the reason for the difference in width of the open-fold zone, as lower strata are more widely exposed on the east.

If the evidences for minor unconformities below and above the Savanna sandstone, as well as at the base of the Thurman sandstone, should prove eventually to be valid and incontrovertible, they would still not constitute proof that the visible Ouachita Mountains were formed during that time. The lithology of these early Pennsylvanian formations is too uniform to admit of such an interpretation. Local warping and some minor folding due to various causes, including perhaps the near-by Arbuckle orogeny, may have taken place throughout this epoch; but the Ouachita orogeny was of large size, overwhelming, and one might almost say catastrophic. There is good evidence that far-reaching crustal changes attended it.

There seems to be nothing whatever about the curving outcrop relations between these two mountain areas that proves the Ouachita orogeny to be of earlier origin than the Arbuckle. The existing relations, as shown by the geologic map, might equally well be cited as evidence for the later age of the Ouachitas. It does not seem at present to constitute critical evidence.

To say that the relatively small amount of chert conglomerates in the Stanley and Jackfork formations of the Ouachita Mountains is critical evidence that the old land of Llanoria could not have been the source of the chert pebbles in the Pennsylvanian formations considered in this paper, is indeed a long jump. The Stanley and Jackfork formations have undoubtedly been transported some distance northwestward from their original place of deposition to their present position. This distance is unknown, but may well be scores of miles. Furthermore, the folding and faulting of the buried southeastern extension of the Arbuckle Mountains, in the edge of Llanoria or bordering it in the Ouachita geosyncline, may have exposed many formations not formerly subjected to erosion.

The assumption that the Ahlosa fault, 3 miles southeast of Ada, is part of the Ouachita orogeny, because it trends east and west parallel with the strike of the middle Pennsylvanian strata at that place, is not, in the writer's opinion, a valid assumption.

The view is held by many that the Ouachita deformation occurred either in late Permian or post-Permian time. So far as the evidences for this conclusion have been presented, they seem to rest chiefly on analogy with the southern Appalachian Mountains east of the Mississippi embayment. Both mountains are strongly compressed into closed and recumbent folds, and similarly faulted by long, curving, low-angle overthrust faults. Miser (9) has recently pointed out that one of the two chief areas of the older Paleozoic rocks in the Ouachita Mountains constitutes a window or *Fenster* where a low-angle fault plane has been locally uncovered by erosion. This feature is also known in the southern Appalachians. The isostatic and Bouguer gravity anomalies are large and negative in both these areas so far as measurements have been made. Only three gravity stations, however, have yet been established in the Ouachitas. All of these analogies, no doubt, are lines of admissible evidence, but they do not constitute critical evidence that the Ouachita orogenic disturbance is of the same age as the later phases of the Appalachian orogeny; hence, late or post-Permian.

NEW EVIDENCE FROM JOINTS

Critical evidence which the writer believes will throw light on the problem of the relative age of the Ouachita and Arbuckle mountains was discovered by field work during the summers of 1928 and 1929. An examination of the *Geologic Map of Oklahoma* shows the Permian strata in the western part of the state resting conformably on, and grading into, the Pennsylvanian strata. Away from the mountainous areas both systems of rock are nearly flat, unmetamorphosed, and dip westward less than 1°.

It has been found that a prominent system of joints radiates fanwise from the curving front of the Ouachita Mountains into the flat rocks of central and western Oklahoma and southern Kansas (Fig. 1). Bedded rocks as high as the middle of the Oklahoma Permian section (Garber sandstone) are cut by these joints. Field work has not been sufficient to determine whether the highest Permian beds are jointed in this way or not. This system is prominent and unmistakable within 100 miles of the outermost large overthrust fault of the Ouachita Mountains. Farther away the strikes are still consistent with the fan shape, but the joints

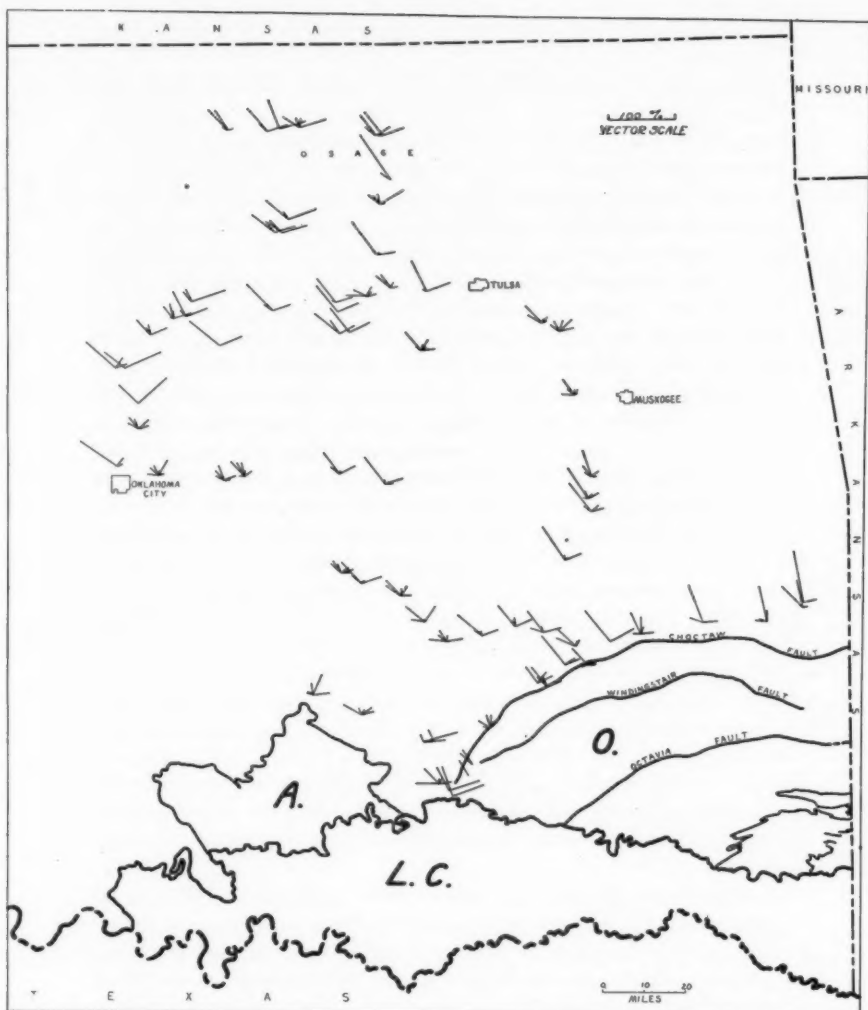


FIG. 1.—Map of eastern Oklahoma, showing the joints at stations in the "open fold zone" of the Ouachita Mountains, as well as in the plains of central Oklahoma. Direction of straight lines indicates strike of joints. Their lengths show the percentage of joints measured at each station. The larger and smoother joints are ordinarily more numerous than the others. However, the true numerical relation is not invariably shown, as the direction of the open cut or outcrop in which measurements were made was in some places a factor in determining the number of joints of different strikes available for measurement.

A northwestward-striking system of joints is obvious; other systems show more or less of the same tendency. Close to the Ouachita Mountains the northwest system is fairly simple and regular. However, farther northwest it is more complex, because of the presence of various sets of joints with slightly different strikes. Notice the radial arrangement of this system. A point near the structural core of the exposed Ouachita Mountains is the center.

A.—Arbuckle Mountains. O.—Ouachita Mountains. L.C.—Lower Cretaceous overlap.

are less smooth, indicating that they were formed under less cubic compression than those on the southeast. There seems to be a gradation from the smooth high-constraint joints near the mountains to the rough low-pressure "fractures" in central and northern Oklahoma; thus, so far as now known, there is no evidence for a two-fold time of origin of this radiating system. There is evidence, however, that the joints of this system were formed with the first important movements which folded and faulted the Ouachita Mountains, for in the zone of open folds skirting the front of these mountains, the joint systems of the steeply tilted beds become identical with those of the flat strata of the plains when the beds and their included joints are rotated back to their original flat position. From the front of the zone of intense folding and faulting outward through the less intensely deformed "open-fold zone," the conclusion is safe that most of the systematic joints were formed at the same time that the flat beds were being first tilted in the process of folding. Still farther away from the advancing mountains the flat strata were jointed, but the stage of folding was not reached. If it is true, as it seems to be in the present stage of the investigation, that there is a real gradation in the "intensity" of this jointing outward from the Choctaw fault into the plains, in such a way that "intensity" is a function only of distance from the mountains, then it follows from the foregoing facts that the tectonic development of the "open-fold zone" took place in post-early (Oklahoma) Permian time. At least a considerable part of the intense orogenic movements of the true Ouachita Mountains must have accompanied the deformation of the "open-fold zone;" hence, this part of the mountainous deformation, at least, is also of post-early Permian age. Very probably all of the more intense phases of the deformation are of this age and not of early, middle, or late Pennsylvanian age, as many have thought.

The writer does not say that all of the major joint systems in the central Oklahoma plains were formed at this time. Only the outstanding, radiating, fan-shaped system is meant. Other regional and some local joint systems are present which may have had an earlier or later origin. Further, as already mentioned, he does not wish to confine all Ouachita Mountain movements definitely to post-early Permian time. Until unmistakable evidence of a double or multiple intermittent orogeny is furnished, however, he takes the position that only minor and relatively inconsequential displacements occurred in the region of the exposed Ouachita Mountains before this time. There is no doubt whatever that an important part of the Ouachita orogeny occurred after early Per-

mian time, and there seems to be a probability that all of it occurred then.¹

A further obvious fact is the lack of any comparable system of radiating joints in the exposed strata of central Oklahoma associated in origin with the later stages of the Arbuckle Mountain orogeny.

In central Oklahoma north and northeast of the Arbuckle Mountains, the joints of the system referred to strike in general about N. 40° W. A careful study of slickensides on fault planes in the western end of the Ouachita Mountains also showed that the median direction of the horizontal projections of about fifty measurements made at well scattered localities fell very close to N. 40° W. The horizontal projections of the scratches on a single fault plane might, of course, have almost any conceivable relation to the true direction of regional movement. But it is believed that the examination of many such measurements ought to show whether there has been a regional movement or not. At least in the region examined there was an obvious median position of the horizontal projection of slickensides. The results justified the assumption. The fact that this median position agrees closely in strike with that of the fan-shaped joint system in a large part of central Oklahoma indicates that the joints formed in line with the direction of compressional movement in the outer part of the earth as the mountains advanced. It further indicates that the extreme west end of the Ouachita Mountains moved northwestward past the buried Arbuckle Mountains and the old land of Llanoria to its present position.

EN ÉCHELON FAULT BELTS

Two other outstanding facts should be mentioned regarding the plains in central and northern Oklahoma northwest of the Ouachita Mountains.

1. The so-called "*en échelon* fault belts" in this region are themselves arranged fan-wise with a point in the western Ouachita Mountains as the center. While there are certain minor variations in strike as they are shown on the *Geologic Map of Oklahoma*, the faults apparently change gradually from a mean strike of about N. 20° W. in Osage County on the north to about N. 35° W. at the south end near the Arbuckle Mountains.

2. The change of strike in the faults is practically identical with the change in strike of the joints in the radiating system already mentioned.

¹The word "orogeny" is used here in its accepted meaning which implies displacements of mountainous type and dimensions, regardless of the fact that the deep-seated causes were developing long before.

The median of many joint measurements in the southern part of the plains was N. 37° W. The agreement in Osage County is likewise close. If more detailed maps were available the writer believes that these faults would be found to be identical in strike with the average of the radiating joints in the same areas. It has been proved that there is agreement within a very few degrees.

The distribution of the radiating joint system is somewhat irregular more than 100 miles from the Ouachita Mountains. In some places the joints are obvious and in others very obscure. They are, nevertheless, ordinarily obvious in localities where the *en échelon* faults are obvious.

These facts serve to tie the so-called *en échelon* faults closer to the Ouachita Mountains in point of origin than has hitherto been done. The faults originated at least as late as the joint system referred to, that is, in post-early Permian time.

McCoy (4, p. 580) contended that this faulting had been completed before the latest Pennsylvanian beds were deposited, because: (1) such faults are practically absent in the limestone region of northern Oklahoma above (west of) the base of the Foraker limestone; and (2) subsurface faults with a similar strike have been noticed much farther west, at Garber and at Blackwell, Oklahoma. The writer, however, feels that this conclusion is erroneous because: (1) faults with similar strike are now known well above the base of the Permian in northern Oklahoma; (2) if the "unfaulted" upper Pennsylvanian formations of western Osage County are traced southward along the strike, strata of similar age are found which are markedly faulted; or in other words, the western limit of the obvious faults, as shown on the *Geologic Map of Oklahoma*, is a line which crosses several hundreds of feet of strata; (3) no prominent unconformity or marked change in depositional history is known in the upper part of the Pennsylvanian of northern Oklahoma, such as would be expected if a large amount of jointing and faulting occurred there at that time; and (4) even if faults are not commonly found in the limestone region of western Osage County, joints with the appropriate strike, on the contrary, are found. They are obvious, tectonic, and regional.

The writer has been forced to the conclusion that the faults and the radiating joints in point of origin are very similar tectonic features, and believes that the so-called *en échelon* arrangement is largely fallacious and unreal. Many faults exist in the plains, with displacements ranging from a few inches to a few feet, which have never been mapped and which are too small to be mapped in the ordinary line of field work. If these small faults were better known, the evidence for *en échelon* arrangement

would probably seem very insecure. In fact, grave doubts as to the reality of the *en échelon* belts are prompted merely from a study of the state geologic map. The "belts" there shown are almost invariably exactly parallel with the strike of the strata. This is exactly where they would be discovered by detailed work along the strike of thin persistent beds—the kind of field work which in the main preceded the making of the Oklahoma map. The belted arrangement of faults is most apparent on this map from Arkansas River southward where thin hard limestones are scarce and are separated by thick series of weak sandstones and shales. It is certain that there are many faults here, concealed in these thick clastic beds, which remain undiscovered and perhaps undiscoverable. In the central part of Osage County in northern Oklahoma, where thin resistant beds are common and where a large amount of detailed work has been done, the faults are arranged in a cluster or group of clusters instead of belts. This is probably the fact farther south in the central part of the state, but lack of sufficient thin persistent strata makes recognition difficult. When viewed from this angle the undoubted *en échelon* belts are reduced to a very few, and even these may be more apparent than real due to neglect of the smaller faults. The evidence in favor of the existence of such belts is thus seen to be much less than commonly supposed.

In the light of (1) the strong probability that these faults are tectonically closely related to the joints of the radiating system referred to, and (2) the fact that the faults themselves display a fan-shaped spread, it seems necessary definitely to abandon the hypotheses which suppose the "*en échelon* belts" to have arisen over deep-seated north-northeastward-trending shear zones in the buried pre-Cambrian complex in consequence of horizontal movement along these hypothetical lines of weakness.

CONCLUSION

1. Black Knob Ridge disappears as the source of the chert pebbles of the early Pennsylvanian rocks in the eastern part of the Lehigh syncline and regions toward the north. Thus vanishes the chief evidential support of the view that the Ouachita orogenic episode is of early Pennsylvanian age.

2. The radiating joints and faults in the plains of central Oklahoma seem to date the Ouachita folding and faulting as post-early Permian (post-Garber sandstone). How much later it may be, remains unknown.

3. At the present stage of the investigation the writer is unable to give a detailed picture of all the factors that entered into the formation

of the radiating faults of central Oklahoma. He feels confident, however, that their origin is much more closely connected with the movements accompanying the Ouachita orogeny than hitherto recognized.

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SIMILARITY OF SURFACE GEOLOGY IN FRONT RANGE OF SIERRA MADRE ORIENTAL TO SUBSURFACE IN MEXICAN SOUTH FIELDS¹

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ABSTRACT

The eastern range of Sierra Madre Oriental, lying west and northwest of the Tampico embayment, is compared with the buried Tamasopo ridge of the Mexican South fields. Observations made at many points along the mountain front are described. A basalt flow associated with the front at one locality and several plugs east and west of it were noticed. At the western entrance to Guayalejo Canyon the El Abra phase of the Middle Cretaceous limestone is overthrust upon the Tamaulipas phase along a plane parallel with the bedding.

The subsurface conditions along the Tamasopo ridge of the Mexican southern district are briefly outlined. The structure and stratigraphy in the area of this buried ridge are very similar to the structure and stratigraphy of the eastern front of Sierra Madre Oriental. The two ridges are interpreted as similar mountain arcs formed on opposite sides of a basin of subsidence during Middle and Upper Cretaceous and Tertiary time.

INTRODUCTION

The Tampico embayment has furnished many interesting problems to those who have studied the stratigraphy and structure of eastern Mexico. One much debated problem which has admitted of no satisfactory explanation is that of the structure and history of the eastern front of Sierra Madre Oriental. Another is the origin of the major structure in the Mexican South fields. The writer believes that these two uplifts have a similar history and that their structures are essentially the same. Both are mountain arcs—the one deeply buried, and the other a surface ridge; both are formed of a reef phase of Middle Cretaceous limestone; both are characterized by stratigraphic and structural anomalies not known elsewhere in eastern Mexico. It is the purpose of the writer to record many observations along the mountain front and to point out the similarity to conditions in the South fields.

The preparation of this paper has been greatly aided by the helpful criticism of C. L. Baker, Paul Weaver, and William A. Baker, Jr., who

¹Manuscript received by the editor, September 28, 1929.

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have devoted many years to the study of Mexican geology and who are thoroughly familiar with the problems discussed. An extensive study of the uplifts bordering the Tampico embayment has been made by C. L. Baker, who kindly read the manuscript and gave many suggestions from his intimate knowledge of the area described. Development of the Mexican South fields has been closely watched during a period of many years by Weaver, who furnished data on the southern continuation of the Sierra del Abra structure. The writer is especially indebted to William A. Baker, Jr., for his courtesy in editing the original manuscript and supplying the information as to results obtained in certain wells mentioned in the paper. Acknowledgment is made of the assistance of G. F. Kaufmann, who has studied the well data in the Mexican South fields and with whom the writer has discussed the subsurface structure and stratigraphy of that area.

The writer wishes also to express his appreciation of the kindness of E. C. Case and W. H. Hobbs of the University of Michigan, who reviewed the manuscript and suggested changes in rhetoric.

GEOGRAPHY OF THE ABRA-TANCHIPA MOUNTAIN FRONT

One hundred and fifteen kilometers due west from the Gulf coast at Tampico, the first range of the Sierra Madre Oriental rises abruptly from the coastal plain. In this area it is named locally Sierra del Abra (Quarry range) from a large rock-ballast quarry at Km. 544 on the Tampico-San Luis Potosi Railroad (Fig. 1). Farther north it is known as Sierra Tanchipa and Sierra Cucharas. The writer applies the name Abra-Tanchipa front to that part of the eastern flank of Sierra Madre Oriental which is in the direct line of the Sierra del Abra, extending all the way from that range on the south to Rio Guayalejo on the north. It commences in the state of San Luis Potosi about 15 kilometers south of Taninul station and extends north and northwest in a continuous ridge for 175 kilometers. In this distance the eastern range of Sierra Madre Oriental is crossed by only three canyons, namely, Abra-Taninul gap, Canton Pass, and Boquillas River canyon. From Atascador ranch north it lies in the state of Tamaulipas.

About 7 kilometers south of the town of Gomez Farias, a low spur of the Abra-Tanchipa ridge forks toward the north and extends approximately 10 kilometers. The spur lies east of the town and is the southernmost ridge east of the Abra-Tanchipa front, which lies west of Gomez Farias and continues northwest, receding from the front of the Sierra Madre Oriental. North of the spur other ridges appear successively

en échelon east of the first. These are parallel with the line of the main Abra-Tanchipa ridge between Gomez Farias and Monte Cristo. North of Monte Cristo the line of the Abra-Tanchipa ridge has a more westward trend than in the south, and appears to cut diagonally across the strike of ridges lying northeast of it.

For a distance of 115 kilometers from its south end the Abra-Tanchipa range is a simple, narrow ridge. The valley west of the ridge is named, in its several parts, from the villages situated in it. They are, from south to north, Valles, Antiguo Morelos, and Chamal. At its north end Chamal Valley becomes shallow, and gives way to a high and rugged range. The Abra-Tanchipa ridge becomes the eastern border of this broad mountain area. The Sierra Nicolas Perez, which lies on the west side of Chamal Valley, passes northward into the western border of the mountain area. Thus, west of Gomez Farias and Monte Cristo lies a great mountain belt 25 kilometers wide, with a high and extremely precipitous east flank which is the northward continuation of the Abra-Tanchipa front. San Lorenzo ranch, 22 kilometers north of Ocampo, is in the main valley west of this mountain belt. The ranches of Joya de Salas and Carabanchel are high in the very center of it. Northward from the vicinity of Monte Cristo and Carabanchel the range tapers in width gradually to Guayalejo Canyon, where it plunges northward and disappears. The steep eastern flank forms a conspicuous topographic feature. The elevation on the crest is estimated to range from 1,000 to 2,000 feet higher than that of the ridges on the east.

From the south end of the Abra-Tanchipa ridge to Guayalejo Canyon, the eastern front of the mountain area is covered with dense vegetation. This effectively conceals much of the geology and makes access to the area very difficult. Observation is limited for the most part to localities where streams have cut across the range or where artificial clearings have been made. A few trails crossing the Abra-Tanchipa ridge, and trails entering the Joya de Salas and Carabanchel make it possible to enter the highest and most rugged part of the range. Good exposures which show the structure and stratigraphic relations along the steep eastern front are rare. The accumulation of rock débris at its base conceals the formation contacts except at a few isolated localities.

OBSERVATIONS ALONG ABRA-TANCHIPA MOUNTAIN FRONT

At its south end the Abra-Tanchipa range appears from surface exposures to be a normal plunging anticline (Fig. 2, *a*). The El Abra limestone dips steeply southeast, south, and southwest in a symmetrical

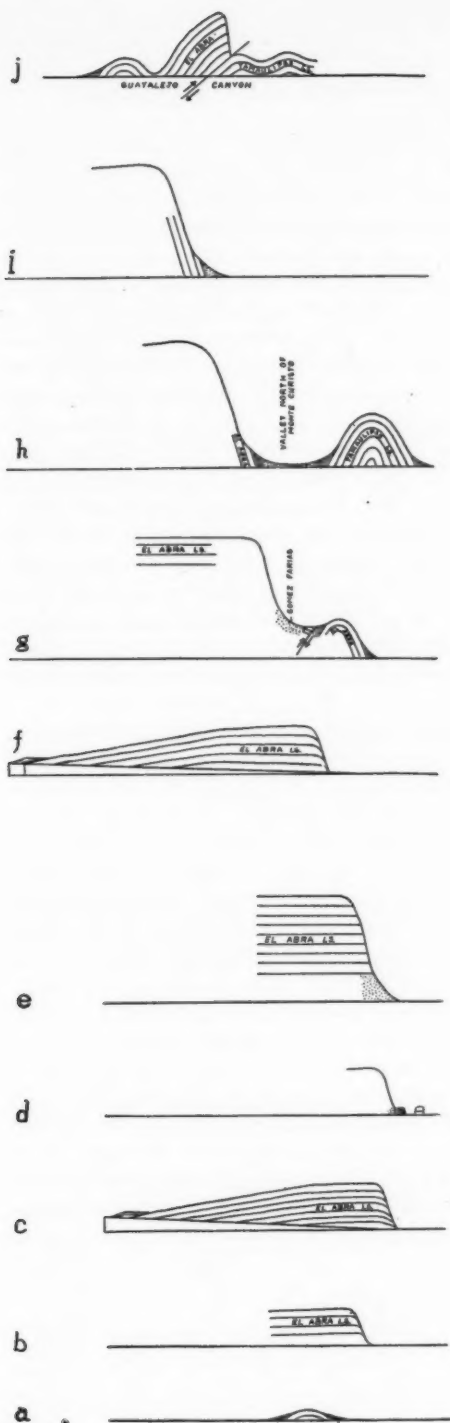


FIG. 2.—Observations along the Abra-Tanchipa front. *a*, south end of Sierra del Abra; *b*, Taninul ranch; *c*, water-gap between El Abra and Taninul stations on the railroad; *d*, Taninul station; *e*, Atascador; *f*, Canton Pass; *g*, Gomez Farias; *h*, valley north of Monte Cristo ranch; *i*, south-west of San Lucas ranch; *j*, west end of Guayalejo Canyon.

nose structure. Overlying the El Abra formation at the east and southeast, apparently in depositional sequence, is the Mendez shale. This relationship is reported to have been observed at ten distinct localities around the plunging terminus of the range. The entire San Felipe limestone formation and possibly the basal Mendez are absent from the section on the east and southeast. On the west, however, the San Felipe formation crops out in contact with the El Abra limestone.

The southern continuation of the Abra-Tanchipa structure has been observed by Weaver¹ on Rio Tampoan at Pujal, where it shows as an anticline in the San Felipe formation. Nine kilometers farther south, near Paso Parrodi, there is a small isolated hill of El Abra limestone in which Choy River rises. This has been interpreted by Weaver as a resistant remnant on the crest of the ridge, which was deeply eroded prior to the deposition of the Upper Cretaceous sediments and is, therefore, below the level of the present surface north and south of the hill. Another interpretation, more in harmony with the southward plunge of the structure, explains this hill of El Abra limestone as a fault block lifted above its normal position. At Santa Isabel, approximately 9 kilometers south of Paso Parrodi, the Compañía Mexicana de Petróleo "El Aguila," S. A., drilled two wells on what was believed to be the same line of folding. They penetrated the El Abra at a depth of 400 feet.

Approximately 4 kilometers north of the southern end of the Sierra del Abra, there is a small, fresh-water spring at the base of its eastern front, on a main road extending southward from Taninul ranch. The El Abra limestone exposed within the spring and on either side of it is light gray, porous, and crystalline, and contains casts of *Rudistacea*. The beds strike N. 15° E. and dip 21° SE. A mantle of black valley soil rests on the limestone exposed at the spring and conceals the contact with any overlying formation. The absence of float from the San Felipe formation, ordinarily conspicuous where present, suggests that the basal Upper Cretaceous is missing in this area.

At Taninul ranch, 3 kilometers south of Taninul station on the railroad, there is a large limestone cave in the eastern face of the Abra-Tanchipa ridge (Fig. 2, b). Although the cave is dry at present, it is obviously a solution channel and probably marks an earlier position of the sulphur springs which now issue from the base of the ridge. The flow of these springs is small, and the water is retained at the point of exit in several small pools, which have been artificially deepened and are used for health baths. The water is whitened by the sulphur content

¹Paul Weaver, personal communication.

and has a strong odor of hydrogen sulphide. The springs are situated approximately 50 feet east of the mountain front, at the margin of the débris which has accumulated at its base. They are of small head, and seep to the surface through a mantle of black soil which conceals their exact source in the country rock.

The Abra-Tanchipa ridge is scarcely 200 feet high at this point, and its elevation decreases gradually toward the south. A talus of large limestone blocks and of soil conceals the base of the steep eastern flank up as high as the mouth of the Taninul cave, which is estimated to be 50 or 60 feet above and 150 feet southwest of the present sulphur springs. The cave has an irregular, gaping mouth, 12 or 15 feet in diameter. Although the cave becomes narrower, it can be entered for a distance of 100 feet or more. The limestone surface inside the cave is greatly altered by solution and redeposition. On a fresh surface, the limestone is white or light gray, coarsely crystalline and very porous. It contains many fossils, chiefly *Rudistacea*, preserved as casts and molds, which have materially increased the porosity. The limestone is in thick, irregular beds. A reliable strike or dip could not be obtained, but there is in general a low angle of dip toward the east. No float from the San Felipe formation can be seen in the débris on this part of the mountain front.

Between Taninul and San Felipe stations, the Tampico-San Luis Potosi Railroad passes through a wind gap in Sierra del Abra. The canyon is approximately 500 feet deep and its walls are nearly vertical (Fig. 2, c). The thick beds of exposed limestone appear very nearly horizontal. At Km. 544, near the west end of the canyon, the El Abra rock quarry is situated on the south side of the tracks. This is the locality from which the El Abra limestone is named. No one of the several openings to the quarry has been designated as the type section; however, the same phase of the formation is exposed in all. The east opening, visited by the writer, is one of the largest. The massive beds of limestone lie nearly horizontal and the exposed vertical section is estimated to be 400 or 500 feet in thickness. At the base it is whitish-gray and is composed chiefly of the minute tests of *Miliolidae*. Scattered through it are small solution cavities partly filled with crystals of calcite and dolomite. Many of the cavities contain a very light, volatile, and almost colorless oil which can be observed only when the rock is freshly broken. At several horizons in the quarry, casts of gastropods were observed. At the top the miliolid limestone is light brownish-gray and compact.

TABLE I
STRATIGRAPHIC SECTION OF ABRA-TANCHIPA RANGE

UPPER CRETACEOUS	<p>MELENDEZ SHALE</p> <p>Gray, calcareous, pencil shales that weather tan; thin interbeds of bentonite; <i>Foraminifera</i> plentiful; massive to poorly stratified</p>	
	<p>SAN FELIPE LIMESTONE</p> <p>Mottled, dark gray limestone, hard, but with shaly texture; beds 2 to 12 feet thick, with thin partings of calcareous shale and interbeds of bentonite; black chert in irregular layers along bedding planes; fossils rare, but <i>Inoceramus</i> in places</p> <p>This formation is locally absent on the mountain front and nowhere attains the thickness found in the Sierra Tamaulipas or in the Panuco section</p>	
MIDDLE CRETACEOUS	<p>Unconformity</p>	
	<p>EL ABRA LIMESTONE</p> <p><i>Miliolina</i> member. Whitish gray chiefly, but locally black or pink; consists almost entirely of tests of <i>Miliolidae</i>; massive bedding; weathers medium gray; thickness 500 feet</p> <p>Taninul member. Whitish-gray, crystalline limestone, very fossiliferous with a varied molluscan fauna preserved chiefly as casts; massive benches 2-6 feet thick</p>	<p>TAMAULIPAS LIMESTONE</p> <p>Very dark, blue-gray compact limestone, with irregular local chert nodules; very few molluscan remains; beds 6 inches to 4 feet thick; weathers medium gray</p>

West of the El Abra quarry, on the south side of the railroad at San Felipe station, Km. 543, the top of the El Abra formation is exposed. The uppermost ledge, 4 feet thick, is black limestone composed almost entirely of *Miliolina* tests. Beneath this is a ledge of flesh-colored miliolid limestone of equal thickness. The beds dip approximately 6° W., and rise eastward to form the Sierra. Although the actual contact of the El Abra with the overlying San Felipe is not exposed at this place, float of the latter formation indicates its presence. The San Felipe formation, consisting of alternating thin beds of limestone and shale, crops out in a cut of the railroad just west of San Felipe station. The limestone weathers a characteristic yellow.

At the eastern end of the canyon, the El Abra limestone is very massive, and as much of the outcrop is concealed by vegetation, the attitude of the beds is not very clear. However, on the south side of the canyon they appear, to an observer on the opposite side, to dip east rather suddenly at the east face of the range. This might be interpreted in one of three ways, namely, as drag along the face of a near-by vertical fault, as the crest of a fold whose steeper east flank has been greatly

eroded, or as surface slumping along either a fault or an erosion escarpment.

At Taninul station, where the railroad leaves the canyon and turns north along the mountain front, the San Felipe and El Abra limestones are exposed (Fig. 2, *d*). Comparatively small blocks of these formations are faulted east of the main escarpment. Their exact relation to the limestone that forms the escarpment is not apparent. Along the east side of the track, the block of El Abra limestone extends for about 100 feet, forming a bench 5 feet above the level of the track, in which two massive beds lie practically horizontal. On the opposite side of the track, scarcely 30 feet away, the block of San Felipe limestone forms a cut bank 3-5 feet high, which extends approximately 150 feet. It consists of alternating layers of limestone and shale whose surface is weathered yellow, for the most part, but locally the shale is red, as if baked. The beds dip 21° SW. toward the escarpment, and strike N. 20° W. This is the southernmost exposure of San Felipe limestone observed on the east flank of Sierra del Abra.

Throughout most of the distance from Taninul to Las Palmas the railroad track is built on a bench of limestone along the eastern face of Sierra del Abra. The track is nearly 100 feet above the level of the plain on the east and gradually descends to that level at Las Palmas station. About 2 kilometers north of Taninul there is a large limestone cavern in the eastern side of the ridge, into which there are two openings, one at the base of the ridge, 50-75 feet below the track, where a large stream of fresh water flows quietly out of its subterranean channel, and another on the ridge 75-100 feet above the track. Although the openings are small, the cavern is large. From the upper opening a steep subterranean trail descends to the stream which flows into the cavern through a much smaller, inaccessible, tunnel-like course. The massive beds of limestone seem to be horizontal, but their planes of bedding are not well exposed.

Approximately 2 kilometers south of Las Palmas station is the opening of the Las Palmas quarry in the east side of Sierra del Abra. The limestone exposed here is white, crystalline, and very fossiliferous, many of the fossils being rolled and corroded. The fauna, including rudistids, pectens, gastropods, brachiopods, et cetera, was determined by Adkins¹ to be of Georgetown age with *Kingena wacoensis* and other Georgetown forms. This horizon is estimated to lie approximately 500 feet stratigraphically below the top of the formation and has been distinguished from the overlying *Miliolina* phase, observed at El Abra

¹W. S. Adkins, personal communication from C. L. Baker.

quarry, by the name Taninul limestone. The term El Abra limestone is used in this paper to include both the *Miliolina* and Taninul phases. The exposure in the Las Palmas quarry is extremely massive, but the indistinct lines of stratification suggest horizontal bedding.

At Las Palmas station the railroad turns abruptly northeast and leaves the mountain front. South of the railroad, at Rodriguez station and at the town of Guerrero, 7 and 14 kilometers, respectively, east of the mountains, two wells were drilled. The well at Guerrero ended in Upper Cretaceous shale. The Middle Cretaceous limestone encountered in the well near Rodriguez was reported to be the Tamaulipas phase and not El Abra, as would be expected from their proximity to the outcrop of the El Abra limestone in the mountain front.

Northwest of Las Palmas, the Abra-Tanchipa range extends approximately N. 20° W. The presence of considerable float of the San Felipe formation on its east side for a distance of 2 or 3 kilometers indicates the presence of that formation in the section in this area.

Canton Pass is a water gap through the Sierra Tanchipa about 75 kilometers northwest of Las Palmas. Between these two points the writer climbed the steep eastern escarpment of the range at three places, namely, at the ranches of Tampacualab, Nombre Dios, and Atascador. The crest of the range rises gradually in elevation and relief from its south end to Atascador ranch, where it is estimated to be 1,500-2,000 feet above the level of the eastern plain (Fig. 2, e). At the three localities examined, a large quantity of débris at the base of the range conceals the geologic relations of the country rock. Above this débris, however, the thick beds of Taninul limestone are practically horizontal and form an almost vertical escarpment. San Felipe limestone was not observed in outcrop or in the float at these localities.

On the Hacienda El Naranjo, about 10 kilometers south of Canton Pass, a spring known as Ojo de Ponzi is situated at the base of the mountain front. The rudistid-bearing Taninul limestone exposed in a small outcrop at the spring strikes N. 55° W., and dips 29° NE. Overlying the limestone and directly in contact with it is brown shale of the Mendez formation. This outcrop is significant for two reasons: (1) it proves the absence of San Felipe limestone in this section; and (2) it indicates that the limestone on the steep east flank of the Sierra-Tanchipa dips eastward.

From Atascador ranch north, the crest of the Tanchipa ridge plunges northward. At Canton Pass (Fig. 2, e), the relief above the valley floor on the east is estimated at 400-500 feet. A cart road from

Quintero to Antiguo Morelos crosses the Sierra Tanchipa by way of Canton Pass. A marked offset in the mountain front on the two sides of the pass and a rather abrupt change in its direction suggest that the position of the water gap may have been determined by structural conditions, such as horizontal shearing or a cross fault. The canyon, however, does not cut perpendicularly to the strike of the range, but is diagonal to it, and somewhat sinuous. To an observer standing in the canyon and aligning himself with the strike of the eastern front, the beds exposed in the side of the canyon clearly dip toward the east. The crest of the fold is very near the east side of the ridge and the limestone beds on the east flank of the fold are much steeper than those on the west, which are practically horizontal. The canyon is 300-500 feet wide, with nearly vertical walls 200-400 feet high. Dense vegetation and soil conceal most of the limestone near the bottom, but the vertical cliffs are bare. The beds of limestone thus exposed are practically horizontal in most of the canyon, although minor flexures and local steep dips are present.

In the Antiguo Morelos valley, west of Canton Pass, the San Felipe limestone crops out. There is a sharp lithologic break between the El Abra, which is black, miliolid limestone in massive benches, and the San Felipe, which is mottled, dark blue-gray limestone in beds a few inches thick and weathered yellow. *Miliolina* persist in these overlying beds, but is not nearly so plentiful as in the El Abra. On the west flank of Sierra Tanchipa the beds exposed in Canton Pass strike N. 20° W., and dip 10° SW.

North of Canton Pass, three trails cross the Tanchipa ridge to Chamal Valley on the west. These connect the following places: San Rafael ranch to Tanquecillos ranch, Hacienda Riachuelos to the village of Chamal, and Guadalupe ranch to Chamal. In this area the ridge is very low. It is estimated to have a relief of 300-400 feet above the level of the plain on the east, and about half that above the level of Chamal Valley on the west. A very thin stratigraphic section is exposed on these trails, as the top of the ridge is practically a dip slope. Light gray *Miliolina* limestone extends across the top of the ridge almost to the eastern side. There, however, it has been eroded from the top of the ridge and rudistid-bearing limestone crops out. The attitude of the beds on the eastern front seems to be nearly horizontal, although the exposures are poor except on the Guadalupe trail, where the massive character of the limestone renders a determination doubtful. In Boquillas River canyon, however, which cuts directly across the ridge west

of Hacienda Riachuelos, the beds have an abrupt east dip clearly exposed immediately at the mountain front. About 20 feet west of it they flatten and are horizontal through most of the canyon. The San Felipe limestone is present on the west side of the ridge in this area, but has not been observed on the east side.

North of the Guadalupe-Chamal road the relief of the eastern mountain front increases greatly within a short distance, and in the vicinity of Gomez Farias is estimated to range from 1,500 to 2,000 feet. Seven kilometers south of Gomez Farias the spur of El Abra limestone, mentioned in a previous paragraph, strikes northward from the main ridge (Fig. 2, g). It is 400 or 500 feet high and extends north about 8 kilometers to Rio Sabinas, where it plunges in a steep anticlinal nose. The structure of the spur is a simple fold. At places examined by the writer, along this fold, the basal Upper Cretaceous formation is missing and the Middle Cretaceous limestone is directly overlain by Mendez shale. Southeast of Gomez Farias, an Indian village situated between this ridge and the high eastern escarpment of the Sierra Madre Oriental, on the trail to Xicotencatl, Baker¹ observed San Felipe with a thin basal conglomerate resting on El Abra limestone. On the trail north of Gomez Farias, where it commences to descend to the valley of Rio Sabinas, a small block of El Abra limestone, on the west flank of the spur, is faulted against the Mendez shale and tilted toward the southeast. The shale-limestone fault contact is exposed in the trail. The displacement is small, and the fault is of no importance in the major structure, but the exposure is significant because it shows that adjustment by faulting as well as by folding has occurred along the mountain front. West of Gomez Farias, a rugged trail ascends to Cameron's ranch and the Joya de Salas. In the canyon along which the trail enters the eastern front of the range, dense underbrush conceals the structure of the limestone. Farther west, where the trail reaches the top of the ridge, the beds are horizontal. These relations are shown in Figure 2, g.

On the left side of Rio Sabinas, about 2 kilometers northeast of the spur previously described, is the southward-plunging end of another anticlinal ridge east of the main front (Fig. 2, h). The Middle Cretaceous exposed in this fold is the dark blue, compact limestone of the Tamaulipas phase. It is overlain conformably by the San Felipe limestone. Monte Cristo ranch is in the valley between the high front of El Abra limestone on the west and the anticlinal ridge of Tamaulipas limestone on the east. Approximately 1 kilometer north of Monte Cristo the San

¹C. L. Baker, personal communication.

Felipe limestone was observed on both sides of the valley. On the west it overlies the El Abra limestone, standing on edge with a steep east dip. On the east side it overlies the Tamaulipas limestone, which dips toward the west (Fig. 2, *h*).

Southwest of San Lucas ranch the beds observed on the steep eastern face of the high range are nearly vertical (Fig. 2, *i*). The crest, west of San Lucas, plunges northward and at the canyon of Rio Guayalejo disappears beneath the valley floor.

At the western entrance to Guayalejo Canyon, on the east side of the Juamave valley, the plunging nose of the El Abra limestone ridge is a symmetrical fold (Fig. 2, *j*). The San Felipe limestone is not present in the section, and Mendez shale rests directly on El Abra limestone. Baker¹ interprets a thin limestone conglomerate, present at this locality, as a basal conglomerate of the Mendez. On the east flank of the plunging nose the El Abra limestone forms a narrow syncline and rises steeply toward the east in an eastward-facing escarpment. At the foot of this escarpment and directly underlying the El Abra is the Tamaulipas phase of the Middle Cretaceous. The contact is interpreted as a thrust fault parallel with the bedding of the formations. The underlying limestone at the contact is black and finely crystalline. The canyon of the Guayalejo from this point east is cut through Tamaulipas limestone which is folded in alternating anticlines and synclines (Fig. 2, *j*).

IGNEOUS ACTIVITY ON EASTERN FRONT OF SIERRA MADRE ORIENTAL

Igneous rock was observed directly associated with the eastern front of the Abra-Tanchipa ridge at one locality. South of Gomez Farias in the V-shaped valley between the mountain front and the diverging spur, there is a small area of basalt. This basalt was extruded subsequent to the development of the present topography and flowed southward down the valley.

On the west side of Sierra Cucharas, at the north end of Chama Valley, there is a small plug of basalt, from which radiate several faults which have brought up and tilted large blocks of El Abra limestone.

Igneous activity in the broad valley east of the mountain front is widespread. In the district of Magiscatzin, about 25 kilometers from the mountains, there is an enormous volcanic plug known as El Sombrero Mountain, north of which, between the towns of Llera and Xicotencatl, a belt of high mesas is capped with basalt. West of Forlon

¹C. L. Baker, "Panuco Oil Field, Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 12, No. 4 (April, 1928), p. 425.

station, on the Hacienda La Clementina, a small basalt plug forms an isolated peak.

The time of these extrusions is post-Cretaceous, but can not be limited more exactly. The deformation of the Sierra Madre Oriental was going on throughout Cretaceous and probably Tertiary time. Although igneous activity probably accompanied the mountain building, the major extrusions were subsequent to the principal deformation. The basalt-capped mesas south of Llera are formed of Upper Cretaceous shale and have a greater elevation than any of the anticlinal ridges of Tamaulipas limestone which lie between them and the high escarpment of the Abra-Tanchipa line. One of these anticlines strikes into the mesa, where its southern extent is concealed by the shale and overlying basalt. The basalt, therefore, flowed out on a shale plain above the buried folds.

MEXICAN SOUTH FIELDS

The important oil fields of the Mexican southern district are situated in a broad crescent which begins on the north in Hacienda San Diego de la Mar and extends to San Isidro, south of Tuxpam River. This line is about 85 kilometers in length, less than 2 kilometers wide, and nowhere more than 45 kilometers inland from the Gulf of Mexico. This line is the so-called Tamasopo ridge, the Dos Bocas-Alamo-San Isidro structure,—the famous "Golden Lane of Mexico." Oil is produced from the top of the Middle Cretaceous in what is known as the El Abra limestone, which is reached at depths ranging from 1,680 feet to 2,583 feet. The stratigraphic section penetrated on the crest of the ridge is extremely variable. Disconformities separate nearly all of the formations, and erosion has locally removed some of the formations entirely, or elsewhere left only a remnant of each. East and west of the ridge all of the formations thicken within short distances, showing that the ridge was a topographic feature, periodically submerged, during most of Upper Cretaceous and Tertiary time. Its relief is only very slightly reflected, if at all, in the structure of the surface strata. The El Abra limestone, which forms the buried Tamasopo ridge, has been channeled and weathered at its crest to form a porous and cavernous reservoir. Contours on top of the El Abra have shown that the productive areas are local hills or structural "highs" which rise above the average elevation of the crest. They also show that the west flank of the ridge is extremely steep and the east comparatively gentle. The northern and southern ends of the ridge have not been definitely located, but drilling has shown that the crest of the ridge is considerably deeper toward the

ends. A system of cross faults encountered along the crest strikes across the axis of the major structure.

Igneous intrusions, such as basalt plugs, sills, and dikes, are common in the line of the South fields.

West of the "Golden Lane" fields the Upper Cretaceous and Tertiary strata thicken enormously, and the depth to the top of the Middle Cretaceous is correspondingly great. Trager¹ has shown that this lowering of the floor of the Upper Cretaceous sea terminates on the north somewhat abruptly along an east-west zone near the southern boundary of the Panuco district, and that the settling took place gradually throughout most of Mendez time. The Middle Cretaceous limestone underlying this area is the Tamaulipas phase. All of these facts may be correlated by the writer's interpretation of the South fields major structure. The depressed zone is a foredeep to the mountain arc of the "Golden Lane" uplift. The deformation was going on throughout the Middle and Upper Cretaceous and probably Tertiary time. This explains the reef development of the El Abra limestone in the shallow sea of the rising arc, and deposition, at the same time, of the Tamaulipas limestone in the deeper waters of the adjacent trough.

The same processes were operating along the western margin of the trough, where the Abra-Tanchipa arc was rising. The evidently shallower depth of the foredeep in that area may be explained in part by the subsequent erosion of much of the Upper Cretaceous shales which were formerly present there, as well as by the fact that the post-Middle Cretaceous uplift was far greater in the west and, therefore, the Upper Cretaceous sea was shallower there than in the east. Displacement along the thrust fault has possibly moved the steep east front of the mountain range across the deepest part of the original foredeep.

The Panuco district is situated east of the foredeep bordering the Abra-Tanchipa arc and northwest of the foredeep bordering the South fields arc. The somewhat abrupt depression along the south side of the district is the first "drop-off" toward the South fields deep.

COMPARISON OF TAMASOPO RIDGE AND EASTERN FRONT OF SIERRA MADRE ORIENTAL

Several stratigraphic and structural conditions which the South fields have in common with the eastern front of Sierra Madre Oriental strongly imply a parallel history. Both are ridges formed of the same reef phase of Middle Cretaceous limestone. The known distribution

¹A. E. Trager, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10 (1926), pp. 686 and 689.

of El Abra limestone outside of these two ridges is confined to the mountain area immediately west of the Abra-Tanchipa front described in this paper.¹ Far more widespread is the Tamaulipas phase which crops out in the Tamaulipas mountains and forms the great mass of the Sierra Madre Oriental north of Rio Guayalejo and, in fact, underlies nearly all of northern Mexico.

The ground plan of both ridges is arcuate. The Tamasopo ridge has a stronger curve, convex toward the west, and the Abra-Tanchipa arc is convex toward the east. The ridges are unsymmetrical with their steeper flank on the convex side of the arc. On the north and south they doubtless extend beyond the point of actual observation, but approaching that point they have an apparent plunge toward the ends.

Their crests are not of uniform height, but have considerable local variation in relief. Most of these differences in relief, at least in the Abra-Tanchipa ridge, are structural, that is, the sectors of prominent relief are those of greater uplift.

The San Felipe limestone is missing above the El Abra throughout a large part of both structures and where locally present is very thin. Along the Sierra Madre Oriental, the Mendez shale rests directly on the El Abra limestone, where the San Felipe is absent. In the South fields, however, the Mendez also is locally absent, and there the Velasco shale or some formation of the Tertiary may rest directly on the El Abra.

Basalt intrusions and extrusions are associated with the uplift in both areas.

These points of similarity are significant and striking. They are strong evidence in support of the theory—if they do not prove it—that the Tamasopo ridge and the Abra-Tanchipa range were formed at the same time, were the result of the same forces, and were formed under nearly the same conditions.

STRUCTURAL DEVELOPMENT

The Abra-Tanchipa range and the buried Tamasopo ridge, with their arcuate ground plan, foredeeps, asymmetrical flanks, and associated igneous activity, are typical mountain arcs. Between them is a depressed area which was a zone of subsidence during Middle and Upper Cretaceous and Tertiary time. The uplift of the marginal regions can be correlated with the depression of the intervening basin. Thrust forces operating in opposite directions on either side of the depressed

¹W. S. Adkins, in 1925, reported El Abra limestone from localities near Orizaba and Cordoba. Personal communication from William A. Baker, Jr.

zone caused differential movement along planes parallel with the bedding of the limestone. The plane of thrusting may have been the base of the limestone series. Horizontal pressure caused the limestone to buckle at the margin of the basin, and eventually to break. The break occurred where vertical differential movement had previously occurred and where the strata were consequently thinner (Fig. 3, *a-c*). Widespread removal of the vertical beds by erosion along the mountain front has exposed the almost horizontal beds observed at the face of the escarpment throughout much of its extent. As one side of the thrust fault moved under or over the other side, a secondary buckling of the strata above the plane occurred locally. This produced a small anticlinal fold at the base of the major overturned front, as observed at Gomez Farias (Figs. 2, *g*, and 3, *f*). Elsewhere there may have been no tendency for the limestone above the thrust plane to buckle. The only folds east of the main front are in the basin limestone, as observed north of Buena Vista ranch (Figs. 2, *h*, and 3, *e*). Where the break took place under relatively less pressure, the limestone may not have buckled; or buckling may have been relatively slight in front of the thrust sheet. Where the break occurred at the crest of the fold, the beds in the escarpment would be nearly horizontal (Fig. 2, *b-f*). The southern half of the Abra-Tanchipa front suggests a condition of this kind. It is believed that the actual advance of the mountain front has been slight, and that most of the horizontal displacement along the thrust plane has been taken up by buckling.

SUMMARY

A summary of the more important field observations and theoretical concepts stated in this paper follows.

1. The El Abra limestone has been traced along a continuous ridge (the Abra-Tanchipa front) from the south end of Sierra del Abra to Guayalejo Canyon on the north.
2. The Tamaulipas limestone forms the core of the ridges which rise *en échelon* north of Buena Vista ranch and east of the main Abra-Tanchipa escarpment. The structure of these ridges is definitely anticlinal.
3. The El Abra limestone and the Tamaulipas limestone are considered distinct facies of a single formation. They are believed to be the result of deposition under conditions which differed chiefly in depth.
4. Where the Tamaulipas phase of the Middle Cretaceous limestone is present there seems to have been continuous deposition of the Middle and Upper Cretaceous sediments, but where the El Abra phase

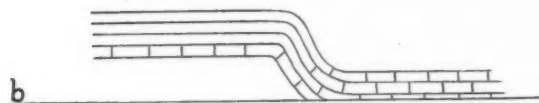


FIG. 3.—Diagrammatic sections illustrating theory of development of Abra-Tanchipa Mountain front.

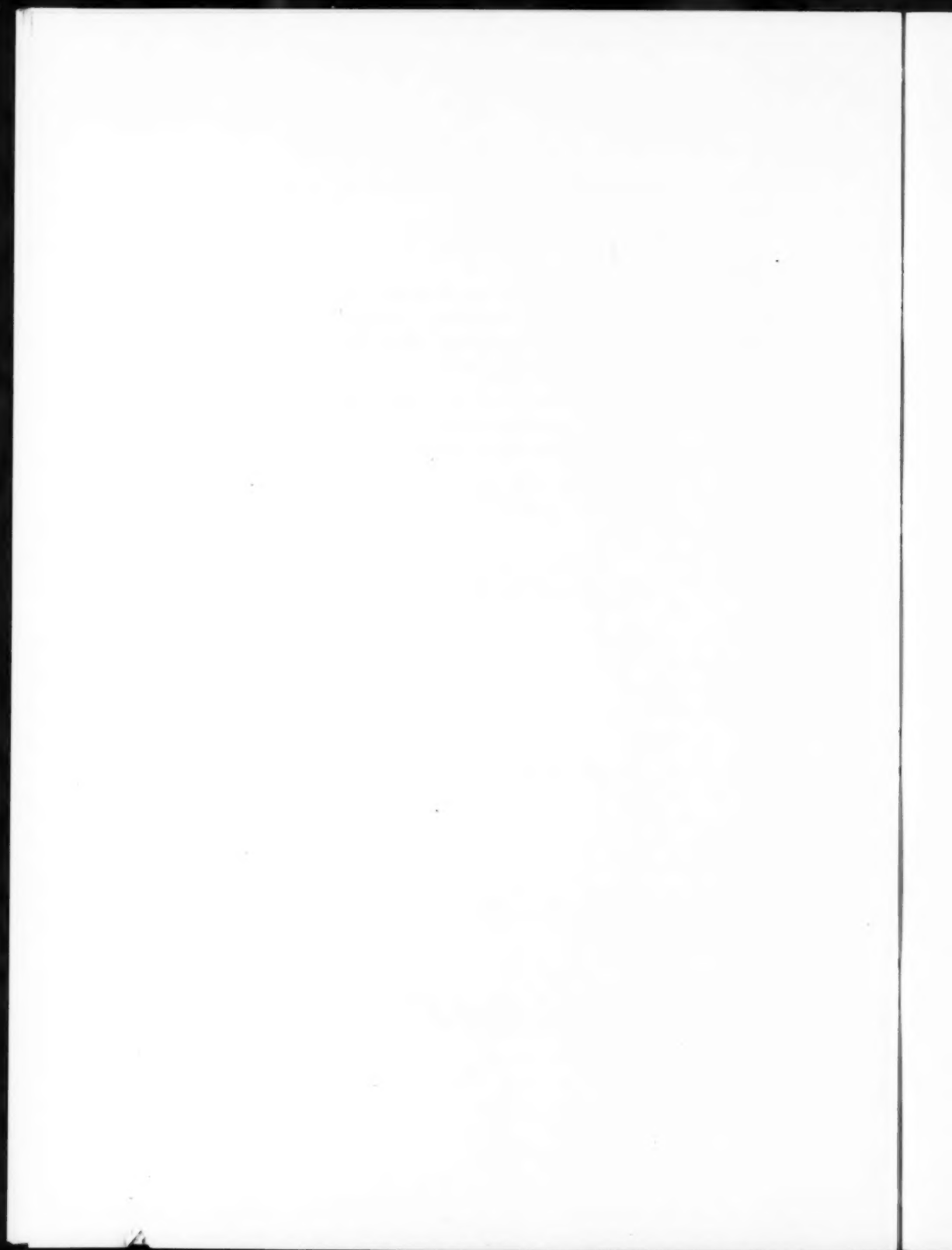
is present a disconformity is recognized between it and the overlying beds.

5. The El Abra limestone, near the western end of Guayalejo Canyon, is overthrust upon the Tamaulipas limestone along a plane parallel with the bedding.

6. The attitude of the beds of El Abra limestone in the Abra-Tanchipa escarpment varies along the mountain front. Near the south end the beds dip east; between Taninul ranch and Canton Pass they are horizontal or have a very low east dip; north of Gomez Farias they are approximately vertical.

7. The Abra-Tanchipa range and the Tamasopo ridge of the Mexican South fields are interpreted as similar mountain arcs formed on opposite sides of a basin of subsidence during Middle and Upper Cretaceous and Tertiary time.

8. The Panuco "high" is regarded as situated in the angle between the foredeeps of the two arcs.



GEOLOGICAL NOTES

GEOPHYSICAL METHODS OF PROSPECTING IN THE UNION OF SOCIALISTIC SOVIET REPUBLICS

At the present time the following institutions and corporations in Russia use geophysical methods of prospecting: the Geological Committee (Survey) in Leningrad, the Emba Oil Trust, the Grozny Oil Trust, the Institute of Applied Geophysics in Leningrad, and the Oil Institute in Moscow. The Geological Survey uses mainly the gravitational, magnetic, and electrical methods (the electrical method especially in mining) as well as the seismological and radioactive methods. The oil trusts until recently worked almost exclusively with the gravitational method. The Institute of Applied Geophysics is studying theoretically various methods of geophysical prospecting. The Oil Institute used the gravitational and magnetic methods for the study of the geological structure of the Apsherone Peninsula. Some results of the theoretical and practical investigations have been published by the Geological Committee, the Institute of Applied Geophysics, the Journal of Oil Operations of U. S. S. R., the Academy of Science of U. S. S. R., the Astronomical Institute in Leningrad, and the *Zeitschrift für Geophysik*.

Being engaged in the investigation of the application of gravitational methods to the study of the structure of the upper strata of the earth's crust, I should like to give a short account of the development of gravitational methods during the last few years.

Field work by the gravitational method is closely connected with theoretical investigations of the problem and with investigations of methods. In particular the following investigations should be mentioned: (1) the effect on the gravitational field of masses of regular shape; (2) analytical and graphic methods of calculating terrain effects; (3) investigation of the particular case of a single limiting surface; (4) the design of a gravitational variometer with three beams; and (5) observations on the Lake Shouvalovo and other tests of the same kind (some of the investigations are already published and others will be published in the near future in the *Zeitschrift für Geophysik*).

Tables I and II give a summary of the progress of the gravitational work carried on by the Geological Committee, and the Emba and Grozny

TABLE I
GRAVITATIONAL INSTRUMENTS IN USE IN U. S. S. R.

Year	1925		1926		1927		1928		1929		1930*	
	T.B.	P.	T.B.	P.	T.B.	P.	T.B.	P.	T.B.	P.	T.B.	P.
Geological Committee	1	..	2	1	2	1	3	1	4	2	12	4
Emba Trust	..	..	2	..	4	1	4	1	4	1	12	3
Grozny Trust	..	..	..	..	..	..	4	..	5	..	7	..

*Information inexact.

Trusts during the years 1925-1928. The gravitational methods were applied in prospecting for salt, oil, coal, and iron ores.

Salt.—The investigations carried on during the years 1926, 1928, and 1929, have shown that in the region of potash-bearing formations in the North Ural Mountains (near Solikamsk) the isogam maps give a complete account of the structure of the salt strata. The estimates of the depth of the salt formation can be made within an error of 10 per cent. Observations in 1928 near Lake Baskunchak (north of the Caspian Sea) showed a region with a very large gravitational anomaly, which depends not only on the structure of the salt formation, but on the deeper strata as well.

Oil.—The observations of 1927-1929 led to the discovery and further study of anticlines of foraminiferal limestone formations on the western coasts of the Caspian Sea in Dagestan.

During the years 1925-1929 a general reconnaissance of an area of 5,000 square kilometers in the Emba district was accomplished, showing the general structure of the salt dome area. Four of the salt domes were studied in detail. The general reconnaissance gave undoubtedly better results than the detailed study of the salt domes, which, in the Emba district, are faulted to a very large extent. It seems that only a combination of several geophysical methods can satisfy the requirements of geologists.

Coal.—The observations of 1929 have shown the importance of a general gravitational reconnaissance for the purpose of the study of the extension of the Donetsk coal district.

Iron.—The pendulum observations in the district of Krivoy Rog supplied new and important data concerning the geological structure of the region and have shown the presence of a second anticline at a distance of about 10 kilometers from the first.

TABLE II
SUMMARY OF RECENT OBSERVATIONS USING GRAVITATIONAL METHODS IN U. S. S. R.

Year	Institution	Region	Area (Sq. Km.)	Profile (Km.)	Number of Stations		Distance Between Stations (Meters)	Geological Structure
					T. B.	P.		
1925	Geol. Com.	Emba	....	4	45	....	30-200	Faults
1926	Geol. Com.	Solikamsk	9	....	109	....	30-250	Relief salts
1926	Emba Trust	Nevogetainsk	325	....	541	10	200-2,000	Salt dome
1926	Emba Trust	Karatom	....	20	60	....	10-1,000	Faults
1927	Geol. Com.	Dagestan	80	....	150	....	500-1,000	Anticline
1927	Geol. Com.	Solikamsk	26	....	592	....	100-300	Relief salts
1927	Emba Trust	Iskine	122	....	455	9	125-500	Salt dome
1927	Emba Trust	Karatom	52	....	249	....	500	Salt dome
1927	Emba Trust	Akat-Kul	....	5	33	....	50-500	Faults
1927	Emba Trust	Lake Shuvalovo	1	....	59	....	50	Bottom of the lake
1928	Geol. Com.	Lake Shuvalovo	1	....	189	....	25	Dissemination
1928	Geol. Com.	Kishtym	0.1	....	100	....	20	Salt dome
1928	Geol. Com.	Baskunchak	1,200	....	168	....	2,000	Anticline
1928	Geol. Com.	Dagestan	15	....	210	....	200-400	Salt dome
1928	Geol. Com.	Emba	8	....	192	....	200	Anticline
1928	Geol. Com.	Krivoy Rog	....	100	....	22	....	Salt dome
1928	Geol. Com.	Solikamsk	....	....	....	21	....	General
1928	Emba Trust	Dossor	120	....	454	....	100-500	Salt dome
1928	Emba Trust	Bec-Bec	6	....	61	....	100-500	Salt dome
1928	Emba Trust	Baychunas	2	....	22	....	100-500	Salt dome
1928	Emba Trust	Reconnaissance Survey	1,500	....	62	9	1,000-5,000	Salt domes
1928	Grozny Trust	North of Terek River	....	200	802	14	250-500	Anticline
1929*	Geol. Com.	Dagestan	75	....	150	....	500-1,000	Anticline
1929	Geol. Com.	Emba	250	....	250	....	500-2,000	Salt domes
1929	Geol. Com.	Solikamsk	10	....	150	....	200-500	Relief salts
1929	Geol. Com.	Donbass	....	100	250	10	500	Anticline
1929	Geol. Com.	Krivoy Rog	....	100	....	45	....	Anticline
1929	Geol. Com.	Chusovaya River	....	500	....	20	....	General
1929	Emba Trust	Reconn. Survey	4,000	....	800	20	1,000-5,000	Salt domes
1929	Grozny Trust	North of Terek River	....	300	1,000	30	250-1,000	Anticline

*Information inexact.



FIG. 1.—The inside view of a half-second pendulum apparatus (Astronomical Institute).

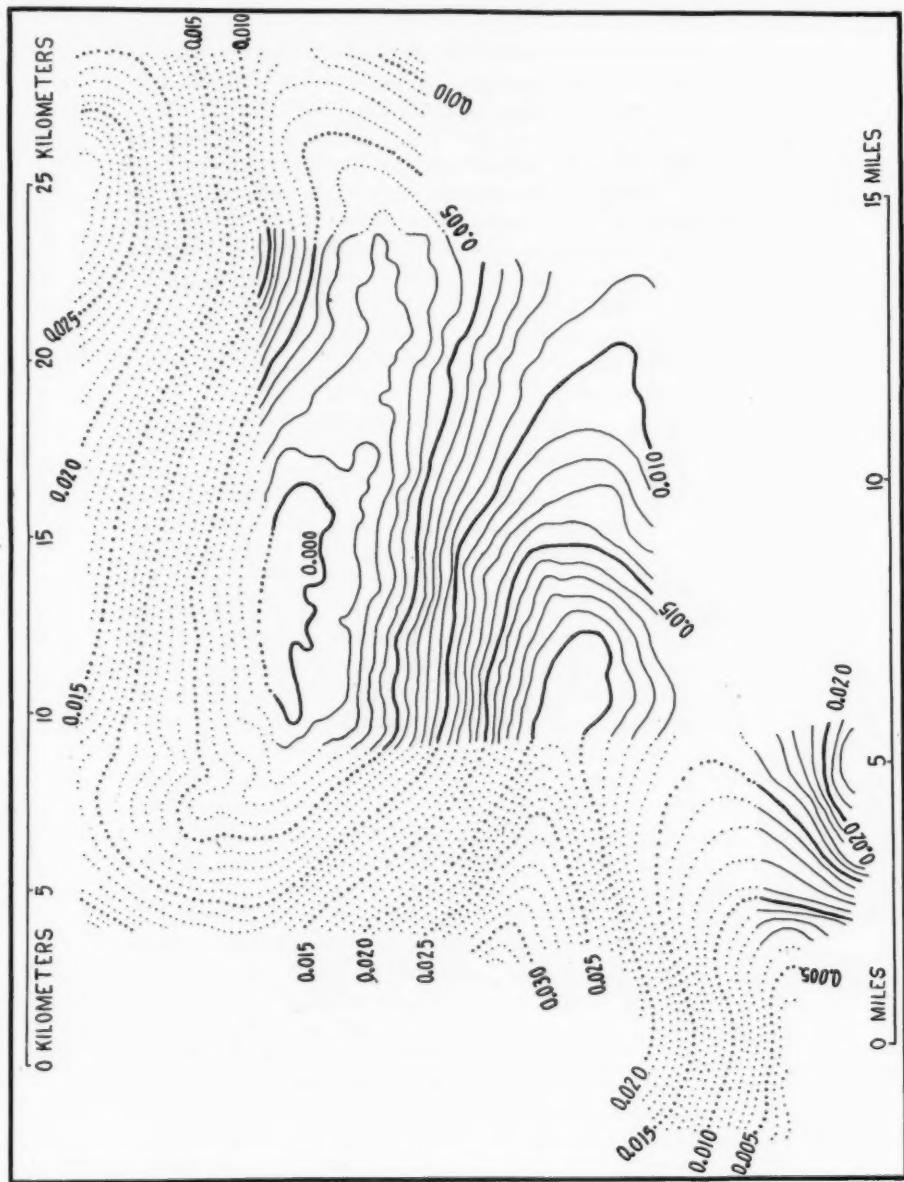


FIG. 2.—Gravity map of Novogatihtsk salt dome, Ural-Emba district, Russia. About fourteen productive wells are included within the rectangular area where gradients are most dense.

First attempts to apply the seismological and electrical methods to the study of the geological structure of oil fields were made in the year 1929. Having in mind the great success of the geophysical methods of prospecting and the large unexplored areas in the Union of Socialistic Soviet Republics, one can expect that in the near future there will be further development of geophysical work, especially in the region of the Caspian Sea, where the flat character of the surface of the earth is well suited to observations with gravitational and seismological instruments.

B. NUMEROV

GEOLOGICAL COMMITTEE
LENINGRAD, U. S. S. R.
December, 1929

SOME METHODS EMPLOYED IN OBTAINING SUBMARINE GEOLOGICAL DATA

Preparatory to the development of a state tideland permit by the drilling of a well on the projection of the surface axis of the Rincon oil field, Ventura County, California, the preliminary work of taking soundings for the construction of a pier was begun. Soundings to the top of the sand in the embayment were of no value, as the piles had to be driven into solid formation; it was therefore necessary to probe through the sand until solid formation was encountered. In so doing it was found that the sand covering was very thin—in most places only a few feet thick—and over much of the area the floor of the embayment had no surface covering at all, reefs being present which could be followed for short distances.

With this information obtained from the diver employed in taking the soundings (Raymond Crawford, of the Merritt, Chapman, and Scott Wrecking Company, San Pedro, California), an investigation was begun by the writer in the hope of being able to trace a few of these reef beds, and, if possible, to locate accurately the anticlinal axis which was assumed to be present. A little study of the situation brought forth two facts which led to the belief that strikes and dips could be recorded. The diver brought up several samples of formations which showed the outcrops to consist of interstratified shales, sandy shales, and fine sands. The outcrops could be broken off in slabs, exposing perfect bedding planes. With this information at hand it was hoped that the recording of attitudes throughout a considerable area would give a comprehensive picture of the structural conditions under water.

It was decided to try to use a Brunton compass under water. There was little probability of local magnetic attraction, for the only magnetic metal in the diver's equipment consisted of a pair of iron shoes, which, due to the position the diver took when readings were taken with the compass, were thought to be far enough away not to affect it.

Before proceeding with the underwater experiment, some instruction was given the diver in the use of a Brunton for recording strikes and dips and in the structural interpretation of outcrops by practical application along various surface exposures adjacent to the coast line in this vicinity. As a result of this instruction, and of the diver's ready comprehension of the problem at hand, one could have confidence in his ability to record properly the attitude of a bed.

The first attempt at taking observations under water was by sealing the compass with paraffine around the edges of the glass. This was unsuccessful because the pressure exerted by the water, even at such shallow depths as 18-35 feet, caused a leakage and partly filled the instrument. The minute sand particles in the sea water also penetrated the compass, and these, together with air bubbles remaining inside with the water, made the reading of the dial impossible; this reading was later found to be difficult under the best of conditions. The next attempt at taking observations was made after removing the glass and filling the compass with fresh water, then replacing the glass, being careful to exclude any air bubbles in so doing. This method on application was found successful.

It may be stated in this connection that visibility under water is very poor. This is due to the fact that the wave action continually churns up the fine silt and sand on the sea floor. A small object can not be distinguished for a distance of more than a foot or two from the diver's helmet and it is necessary to have the helmet practically in contact with the compass in order to read it.

In order to obtain comprehensive pictures in cross section of the structural conditions under water, the submarine prospecting was confined to the immediate vicinity of lines run out from shore at chosen intervals. These lines were established normal to the strike projected from shore. Base lines were measured on shore, and, by means of transit intersections, recorded observations under water were accurately tied to the land control. Thorough prospecting was done along these lines and observations recorded where possible within intervals not exceeding 200 feet.

This submarine prospecting was done from a 65-foot tug boat especially equipped for diving work. A spar would be located at a point on line at which an observation was desired, the spar being flagged in from the ends of the base line on shore. The boat was then anchored into position adjacent to it.

The diver would then go under to look for an outcrop. If there happened to be one present the problem was simple and would merely consist of breaking off a few slabs of rock and taking a reading. Ordinarily, under such fortunate circumstances, several readings would be taken along the strike to make possible the recording of an average attitude. In most places, however, sand would have to be cleared away to find an exposure. The diver would first probe with a high pressure jet. It was found that observations could not be obtained where the sand covering was in excess of 30 feet. Where it was less than this, the diver would wash out the sand with his jet for a distance of 20 or 30 feet along the strike and for 5 or 6 feet across it. This operation would ordinarily consume an hour or more. Then he would come up for the compass, wait a short time for the water to clear to its normal cloudiness, and then go down for a reading. With good fortune he got it, or perhaps several; but in many places the wave action would be such as to refill the hole he had made and bury the formation exposed, so that the jetting operations would have to be repeated two or three times before the strike and dip could be recorded. When a record was finally made, a spar was again set and the point located, for the point finally taken might be a little distance away from the original spar set on line.

After completing one observation the boat crew would slack up on the two stern anchors and move off shore for a distance of 100 or 200 feet; then the diver would go below and begin the probing operations once more. Two observations showing two strikes and dips were considered a good day's work.

On a few occasions a medium or coarse sand stratum would be encountered which showed no bedding, in which event the labor of getting into position, probing, and jetting would be lost.

The conditions under which the diver had to work while actually recording an attitude are worthy of mention. It is difficult while under water to keep oriented. In most places one can tell off-shore from in-shore by the difference in the wave action, but it is not everywhere possible to do that. Because the sea is continually rolling along the bottom, the diver, in order to keep in position, must let most of the air out of his suit; in other words, make himself heavy so that he can lie

prone and not be churned around. Due to the difficulty of keeping oriented it was found necessary to record the direction of dip rather than the strike, leveling the back of the compass instead of the side against the bedding plane, then reading the north end of the needle. Likewise in reading the amount of dip, it was found more feasible to use the back of the compass, thereby reading the complement of dip and later converting. In order to facilitate reading the compass in this manner the top had previously been removed.

The net results of the work were extremely gratifying after three weeks of this moving into position, probing, and jetting. It was possible to have most points located less than 200 feet apart along established lines of cross section.

The axis was located at several points and it was possible to record a sufficient number of attitudes on both flanks of the fold to be sure of the results. The uniformity of strike along each individual line was such that it left no doubt as to the amount of plunge at each point on crossing the axis. A further check on the axial trend was indicated by the gas bubbles breaking on the surface of the water, and occurring along the axis as plotted.

A short time after this work was done the writer flew over this area at a time when the wave action appeared to be at a minimum, and found that the submarine growth of kelp weed had a definite alignment. This is in accord with the fact noted while doing the submarine work that the kelp is attached to the sandy phases of the strata. It is possible, therefore, that in areas where kelp is growing, beds might be traced by the mapping of kelp growth. It is the writer's understanding that this has been done in determining the undersea structural conditions in other areas along the California coast.

It is entirely possible that many submarine areas of geological interest can be partly mapped through close observations, with perhaps small variations in the methods pursued to fit local conditions. To obtain strikes and dips, however, the sand covering on the sea floor must be at a minimum.

LEO S. FOX

GENERAL PETROLEUM CORPORATION
OF CALIFORNIA
LOS ANGELES, CALIFORNIA
November, 1929



DISCUSSION

STRUCTURE CONTOURING

Books and treatises usually beget others without adding much that is new. For this reason, and for many others, it does not seem opportune to attempt a treatise on the subject of contouring initiated by R. E. Rettger. In his geological note, "On Specifying the Type of Subsurface Structural Contouring," appearing in the December *Bulletin*, the contouring of subsurface maps is divided into three types—each illustrated. He names them (1) mechanically spaced contouring, (2) parallel contouring, and (3) equi-spaced (equi-dip) contouring. These he respectively defines as very conservative, less conservative, and radical.

Structure contouring is a graphic attempt to delineate the folding set up in the outer shell of the earth by the forces of nature. The science of geology is concerned with the actual data. The art of geology is concerned with the casting of the more or less chaotic data into their true form and significance. This is not necessarily confined to conservative processes of analysis and types of solution. Unhampered analysis and solution strive for the truth. They do not hesitate to seize the radical processes, if necessary, realizing that the radical processes of to-day may become the predictors of to-morrow's happenings. Nor does it seem probable that oil companies prefer type 1—mechanically spaced contouring—which Rettger states may completely eliminate the personal factor of imagination and bias. As a matter of fact, the terms "imagination" and "bias" do not seem to be properly used in the description of mechanically spaced contours. Imagination is an attribute of common sense, bias of conservatism. Oil fields are discovered as a matter of common sense enterprise, and overlooked as a matter of conservatism. Conservatism may be the defense of indecision or an attempt to retreat from a bad position, as well as a means of eliminating all but the more logical arguments that may be presented.

In a paper read before the Tulsa Geological Society in November, 1928, the writer recognized two processes of contouring and designated them as mechanical and interpretative. Present-day exploration for new oil fields is largely based upon well-log data and geophysical anomalies. As such it is and will remain largely interpretative, incorporating the basic types and impulses of human nature. To be effective, the interpretative process must be creative. To get the most out of the process it must be somewhat extreme—the word extreme being used in the same sense that the procedure of the first surgeon who plunged a knife through abdominal walls to restore the health of an ailing man was undoubtedly extreme.

Structure contours are not mere lines on paper; they are the graphic expressions of structural facts, interpretations, and conclusions. They may represent the naked facts, or they may be clothed with speculation. Practical application of the process of contouring consists not of observation alone, but

includes ability to interpret and to project; ability to survey problems in their entirety; ability to grasp the unity and significance of the data; appreciation of human limitations; and a sense of balance and perspective. Contouring may be mechanical, directed by geometric processes; or it may be interpretative, guided by inductive and deductive processes of logic. Briefly, contouring is the art of geologic mapping.

The mental processes that guide and direct contouring are not allotted to man by the rules and regulations of society; rather, if one believes the psychologists, man is guided and directed by his emotional attitudes, and he belongs to one of three classes, designated as introvert, extrovert, or ambivert. Perhaps a fourth classification is in order for the promotion geologist, which might be designated as pervert. These classes of emotional attitude are the great misfortune of geology, in that they delineate the native ability of the man and may set up in him prejudices of the senses. They alone are the true makers of class or caste. But it is fortunate, in the nature of things, that correct interpretations of structural data are rare, else all the oil would be discovered overnight and the industry would be lost in the deluge.

Structural geology, like all other human endeavor, emerges from a philosophy, advances to a science, and culminates as an art. As a philosophy it seeks to explain natural phenomena by trial theories. As a science it describes the fully revealed structural facts and interprets them in the light of trial theories that have withstood the fire of criticism. As an art it applies scientifically deduced principles to give form to obscure structural data—even though the resultant work may seem to rest on no substantial foundations.

Structure contouring is concerned with the creation of structural forms. Even if all the facts of a geologic problem are at hand, they can not always be cast into their proper form or composed into a balanced picture. The process of contouring is not the simple problem that textbooks, without exception, make of it; rather, it is highly involved. The rules of textbook procedure fail of practical application. The textbooks solve examples of three points not on the same straight line and on the same plane surface; but they fail to show how to prove that three scattered geologic points lie on the same plane surface. As a matter of fact, the geologist is constantly called upon to analyze structural data consisting of many points of attitude any one, two, three, or all of which may lie on different surfaces—some plane, some curved, some inclined in one direction, some inclined in other directions, some horizontal, and others vertical. He must determine—sometimes correctly, more often incorrectly—the plane on which each point lies.

The solutions of structural problems differ most out in the shadowy borderlands of insufficient data. The making of a contour is readily followed, but there is nothing in which geologists may differ more than in the interpretation of structural data. The data may be uniformly spaced, they may be plentiful, and of equal value, but the resultant picture or form is not at all in conformity with the one created by the physical forces of nature. Many maps of the same area show a wide latitude of expression. Some conform with the structural habit of the area or province, others do not. Some are clear, showing the application of scientific principles and multiple working hypotheses to the observed facts. Others are vague and confused—the perplexed expressions of

mechanical efforts. There are, in the main, two types of structure contour maps, and two processes whereby a structure contour may be brought into materialistic expression. One picture is created by skilful technique that combines the daring of youth with the discretion of maturity, and methods of scientific investigation with the temper of experience. Robot efforts, guided by mathematical solutions employing geometry and trigonometry, present another picture. Many times both types fail to delineate the existing natural form, resulting in inverted high or low structural forms, and in unexpected dry holes or production. It is a simple matter to delineate geologic structure if all the controlling key-bed elevations are known. It is another matter to seize the story, its facts as well as its inferences, if many of the critical data are missing. Next comes the applying of creative interpretative procedure, making free use of the philosophy and science of the problem, shaping the scattered data into logical structural forms bearing the habit characteristics of the known forms of the district. But there are no fixed methods of procedure, to be indiscriminately applied, whereby this may be accomplished—it is to be achieved by patient and deliberate labor and much daring.

Structural pictures depend largely upon the soundness of the premises from which the contouring starts. The process of contouring is initiated by gathering all the available geologic data of the district or province in which the area to be investigated lies. The data are classified, and briefs prepared. The validity of the brief arguments is supported by actual evidence. The evidence is subjected to careful inductive and deductive analysis. Structural data are analyzed individually and by groups. Individual cases are then collected into classes, and for each class general principles are developed from the brief. These principles are sound only if the principle is valid, if the problem is subject to the principle, and if all factors of cause and effect are common to the principle and problem. The resultant map is correct if it truly portrays conditions in the area concerned. The assumed rate of dip between points, more than any other factor, determines the correctness of the map. As the assumed rate of dip becomes less than the true rate, the number of indicated structures become less than the number actually present, and the data assume amoeboid forms; as the assumed rate of dip becomes greater than the true dip, the number of indicated structures becomes greater than the number created by the forces of nature. The process and type of contouring that most closely approximate the natural form should be used. As Rettger concludes, "it is not possible to state which method or combination of methods is the best to use, since no one type is correct to the exclusion of the others."

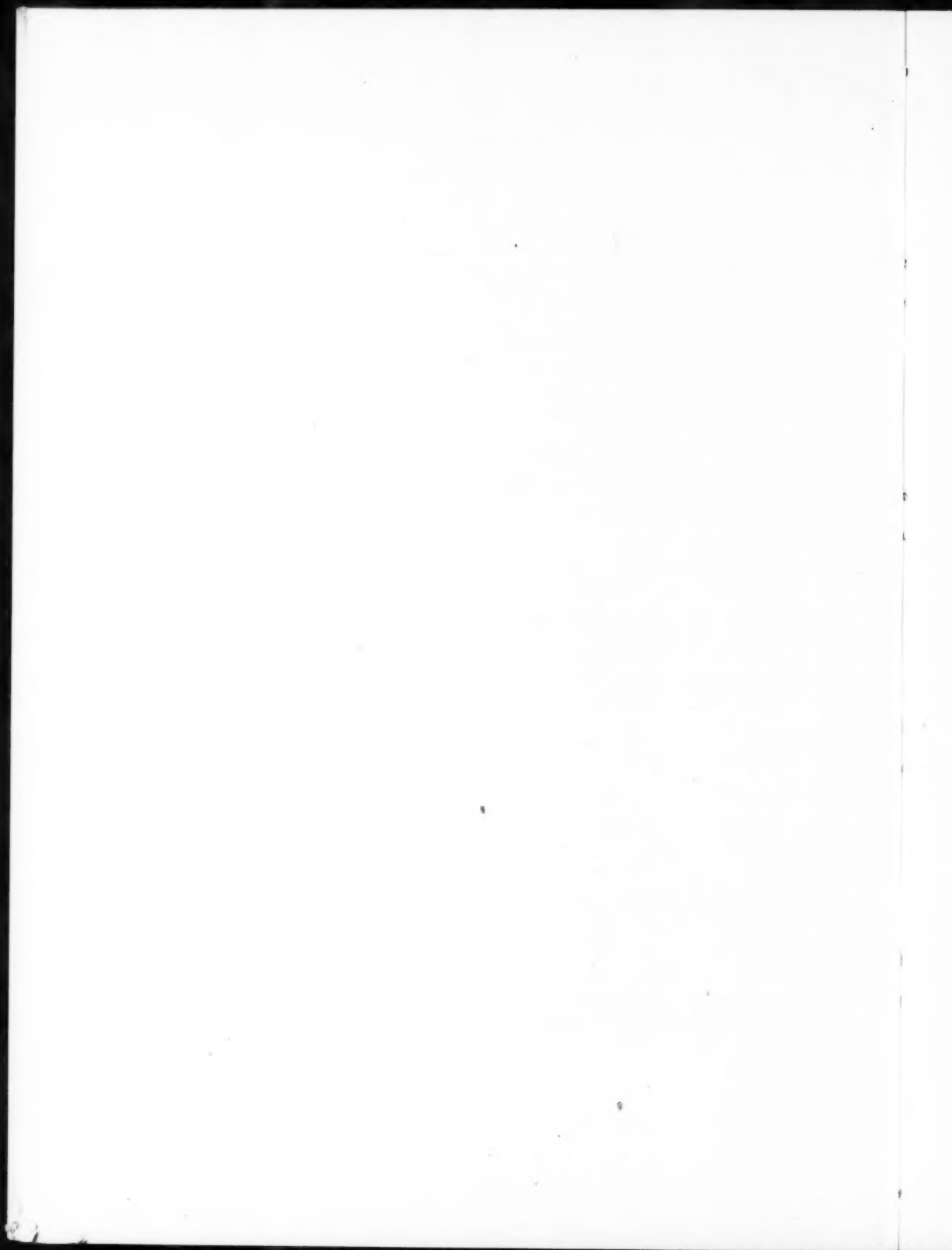
HENRY A. LEY

TULSA, OKLAHOMA
December 16, 1929

CORRECTION

TEMPERATURE GRADIENT IN PECHELBRONN, ALSACE

In Professor Alfred C. Lane's discussion on page 1569 of the December, 1929, *Bulletin*, the name "Butler's" in line 5 should be *Bailey Willis*'.



REVIEWS AND NEW PUBLICATIONS

"Experiments in Connection with Salt Domes." By B. G. ESCHER and PH. H. KUENEN. *Leidsche geologische Mededeelingen* (1929), Deel III, Afl. 3, II, pp. 151-82, Pls. 20-38.

The experiments consisted in a laboratory study of the deformation of layers of paraffine, or of alternating paraffine and clay under pressure from a ring-shaped disc, (1) with no pressure on the central area, and (2) with a counter pressure on the central area of one-half that on the disc.

In the first series of experiments, roughly congruous folds formed if the layers were of identical plasticity, but if layers of different plasticity alternated with each other, the folding consisted of smaller complicated disharmonious folds superimposed upon larger ones corresponding with those just mentioned. Part of the folding was in the form of vertical crenulate folds. In the second series of experiments, a remarkable series of folds of M-shaped vertical cross section were obtained. Studies of the stream of flow seemed to show that friction between the paraffine and the iron wall of the compressing disc exercised an important influence upon the flowage of the paraffine. If the cakes were composed of several layers, sliding planes developed, and if the layers were of different plasticity, tangential fissures were formed at right angles to the direction of flow. Thickening of the layers in the crest of the dome, in some real and in others relative, was found in some of the experiments. The authors state that "The principal result of the experiments is that all shapes of folds observed in the German salt domes can be completely explained by Lachman's theory; that is, by the isostatic pressing up of the specifically lighter salt in pillar-like masses. This alone, however, does not exclude the possibility that tangential pressure may be partially or entirely responsible for the known phenomena," as flowage of salt toward the dome will take place under both tangential and isostatic pressure.

This interesting series of experiments, strictly speaking, should be regarded as a study of a very limited phase of salt dome activity, that of the flowage of the salt series in the extreme diapiric phase of salt-dome activity, in which a semi-cylindrical salt core is intruded into sediments not under differential tangential pressure. The conditions of the experiment do not simulate the geological conditions of the non-diapiric or only faintly diapiric salt-dome ridges of the Magdeburg-Halberstadt basin in Germany or the geological conditions probably prevailing at the roots of the diapiric salt columns. The results of the experiments are distinctly suggestive and are an important contribution to salt-dome theory. The most suggestive thought is that the crenulate marginal folding at such German domes as Benthe is not necessarily the result of tangential compression. The M-shaped folding interests the reviewer, as for years he has tried to think of some logical way of getting slightly greater circumferential than central uplift of the crest in order to explain the

doughnut-shaped topographic mounds of the Vinton and Barbers Hill domes, and the peripheral ring of elevations on the top of the cap rock of such domes as Bryan Heights and Belle Isle.

This line of research seems worthy of further exploration, preferably with the experimental conditions approximating more closely those geologic conditions which give rise to non-diapiric or only faintly diapiric salt domes and salt-dome ridges, and preferably with the purpose of determining if any experimental clue can be obtained to the differences of character of domes formed under isostatic and under tangential thrust.

Another line of research worth following is a quantitative mathematical investigation of the competence of the possible isostatic thrust to account for the upthrust of the salt. The geological factors of such an area as that of the coastal salt-dome area of Texas and Louisiana should be weighed carefully; on some domes, the uplift of 1,000 feet of cap rock, mostly anhydrite with a density of 2.8-2.9, must be accounted for. On most domes a considerable prism of sediments has been uplifted a considerable amount. Friction must also be evaluated at least approximately.

The structure around some of the East Texas domes¹ suggests the possible rise of a buoyant block in a semi-liquid.

DONALD C. BARTON

HOUSTON, TEXAS
December, 1929

"Notes on Lower Tertiary Deposits of Colombia and Their Molluscan and Foraminiferal Fauna." By F. M. ANDERSON. *California Acad. Sci.* (San Francisco), Vol. 17, 4th ser. (June, 1928), pp. 1-29, Pl. 1, 11 figs. Price, \$0.50.

Extensive Cretaceous earth movements developed a great system of mountain ranges, with intervening valleys and coastal lowlands. Subsidence in early Tertiary was attended by advance of the sea in which contemporaneous sediments were deposited far inland. Up the valleys marine environment gradually merged with estuarine. Locally lagunal environment prevailed even on the present high mountain ranges. Tertiary deposits rest on Cretaceous beds, igneous rocks, and metamorphics which may be, in part, of Paleozoic age.

Marine Eocene.—The Eocene deposits of the lower Magdalena valley are almost entirely marine. Coal-bearing strata suggest temporary non-marine environment. The Eocene deposits include cherts, limestones, shale, sandstone, and conglomerate. Fossils are present in some beds.

A stratigraphic and structural section of the Eocene near El Carmen, where 4,500 feet of Eocene is exposed, is given in detail, as well as information of the occurrence and general structure of the Eocene in the Department of Bolivar. Correlation of the sections of Anderson, Beck, and Werenfels is given in tabular form.

¹E. A. Wendlandt and G. Moses Knebel, "Lower Claiborne of East Texas with Special Reference to Mount Sylvan Dome and Salt Movements," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13 (1929), pp. 1347-75.

Oligocene.—Oligocene deposits are briefly discussed, but will not be mentioned here, as a more comprehensive discussion is given in a subsequent publication.¹

By far the largest part of the publication is devoted to a description of the mollusca, which will certainly be welcomed by those interested in the paleontology of the Antillean region.

J. M. WANENMACHER

NEW YORK CITY
November 18, 1929

"Marine Miocene and Related Deposits of North Colombia." By FRANK M. ANDERSON. *Proc. California Acad. Sci.* (San Francisco), Vol. 18, 4th ser. (1929), 109 pp., Pl. 16. Price, \$1.50.

PRE-MIOCENE

Poso series.—A series of clastics consisting of coarse to fine sandstones, sandy shales, shales (locally carbonaceous), and minor amounts of conglomerate. Fossils are rare. Locally, as much as 3,400 feet of these strata are exposed. The series furnishes numerous oil and gas seeps as well as mud volcanoes. Petroleum is believed to be mostly indigenous, though it may have originated in part from underlying Eocene strata.

The Poso series is ordinarily highly inclined as a result of folding and faulting. It rests unconformably upon fossiliferous Eocene and is in turn overlain by fossiliferous Miocene. The Poso series is tentatively assigned to the Oligocene, as it is probably the equivalent of strata definitely Oligocene in other parts of the Antillean region.

MIOCENE

Miocene deposits are extensive in northern Colombia, though not as widespread as formerly believed. They are marine and are divided into the following groups: (1) Galapa (La Popa) (1,650 feet); Tubera (2,650 feet); and Las Perdices (1,000 feet).

Las Perdices group.—This consists of clay shales, sandy shales, cherty and siliceous beds, and some sandstone. The shales contain many fossils, a preliminary determination of which places them near the base of the Miocene.

Tubera group.—Overlying, probably disconformably, is the Tubera group, which consists mostly of incoherent sandstones and sandy shales. Locally it is divisible into non-persistent lithologic members.

Galapa-La Popa group.—Seemingly this group does not cover the general areas of older Miocene, but is local, being found only near the present coast in two localities. In these places it is conformable upon the Tubera group. At La Popa it consists of incoherent sandy shales and clays with marl layers; near Galapa it is calcareous sandstone.

PLIOCENE

Coral limestones and incoherent clastics occur at intervals near the coast. Evidently they do not everywhere rest upon Miocene strata, and where they

¹F. M. Anderson, *California Acad. Sci.*, 4th ser., Vol. 18 (1929), pp. 74-86.

do the relations suggest, though they do not prove, unconformity. Locally more than 900 feet of Pliocene strata are present.

The author gives much detailed information concerning the occurrence and attitude of the different groups in several localities. A wealth of paleontological information is included as well as a table showing tentative correlation with deposits of other Antillean localities, Florida, and Europe.

J. M. WANENMACHER

NEW YORK CITY
November 18, 1929

"Geophysical Investigations at Caribou, Colorado." By C. A. HEILAND, CHARLES W. HENDERSON, and J. A. MALKOVSKY. *U. S. Bur. Mines Tech. Paper 439* (Washington, D. C., 1929). 45 pp.

This technical paper constitutes the second part of the U. S. Bureau of Mines' report on the results of the geophysical investigations at Caribou.

The object of these investigations was to determine the effect of a geologically known deposit upon a number of geophysical methods.

The geology of the area under investigation is described by Charles W. Henderson. The main feature is a gabbro intrusion in a monzonitic country rock. In this gabbro, a magnetite deposit was formed, presumably by magmatic segregation, consisting of a network of titaniferous magnetite bands and schlieren. The object of the geologic survey was to outline the areas of greatest magnetite concentration.

A detailed plane and topographic survey was made by J. A. Malkovsky and the reviewer, in order to furnish the necessary geodetic data for the location of the stations, and in order to correlate the topographic with the geologic and geophysical data.

Electrical prospecting was applied by A. S. Eve and D. A. Keys, using the following methods: (1) self-potential measurements; (2) measurements of equipotential lines, with point- and line-electrodes, using both D. C. and A. C.; (3) electro-magnetic (induction coil) measurements, the primary current being galvanically supplied by point- and line-electrodes; (4) the same measurements, the primary current being supplied inductively by a circular or rectangular coil; and (5) so-called "leap-frog" resistivity measurements. The data obtained were in agreement with the results of the geologic, magnetic, and torsion-balance survey and were published in the first part of the U. S. Bureau of Mines' report on the geophysical investigations in Caribou (*U. S. Bur. Mines Tech. Paper 434*).

The magnetic measurements were made by J. A. Malkovsky and the reviewer on 182 stations. Schmidt's magnetometers were used throughout. Their sensitivity was decreased to approximately 1/10 of their ordinary value by the use of gold-screws. The magnetic picture of the extremely strong magnetic anomalies is very irregular and corresponds with the chaotic arrangement of the magnetite veins.

A special chapter is devoted to the discussion of negative magnetic anomalies that had been observed.

Unfortunately, the results of the torsion-balance measurements could not be published in this report. They are in remarkable agreement with the re-

sults of the geological, electric, and magnetic survey, if one considers the extremely rugged topography, the slopes of the hill in places being as much as 20°. A graph representing the results of torsion-balance, electric, and magnetic survey on a part of the deposit may be found on page 44 of the *Colorado School of Mines Magazine on Geophysical Prospecting*.

Furthermore, the publication of a number of photographs and charts pertaining to the results of the topographic and magnetic survey was, unfortunately, not possible. The reproduction of the published charts is not as good as the authors had expected. Through an error of the printer, the scale was left off these charts. For the plan of stations shown on page 6 of the report, a distance of 100 feet corresponds with approximately 9 millimeters.

C. A. HEILAND

GOLDEN, COLORADO
December 20, 1929

RECENT PUBLICATIONS

ALASKA

"The Chandalar-Sheenjek District, Alaska," by J. B. Mertie, Jr. *U. S. Geol. Survey Bull. 810-B*. (Supt. Documents, Washington, D. C.), pp. 87-129, Pls. 1 and 2 (maps), Figs. 1 and 2.

CALIFORNIA

"The Kettleman Hills Oil Field," by Carl H. Beal and A. H. Heller. *Oil Bulletin* (Los Angeles, California, December, 1929), pp. 1289-95, 5 illus.

"Report on Kettleman Hills Oil Field," by E. H. Musser. *Oil and Gas Jour.* (Tulsa, Oklahoma, December 12, 1929), pp. 98-99, 102-03, 1 map, 1 geological cross section.

CANADA

"Crude Petroleum in Alberta," by T. A. Link. *Petroleum Times* (London, November 23, 1929), pp. 998, 1000.

CROOKED HOLES

"Magnetic Compasses in Well Survey," by Frank Rieber. *Oil and Gas Jour.* (December 5, 1929), pp. 143, 146, 190-91, 16 figs.

"Offers Straight Hole Drilling Theory," by J. T. Hayward. *Oil and Gas Jour.* (December 5, 1929), pp. 57, 228, 2 figs.

"Inclination Record Obtained Each Time Tools Are Pulled," *Oil Field Engineering* (Philadelphia, Pennsylvania, December, 1929), p. 37, 2 figs.

"Johnson-DeFleurs Surveying Instrument," *Oil Field Engineering* (December, 1929), p. 53, 1 illus.

"Straight Hole Drilling Practice," by John Franklin Dodge. *National Petroleum News* (Cleveland, Ohio, December 11, 1929), pp. 45-49, 4 figs.

GENERAL

"The Contact of the Fox Hills and Lance Formations," by C. E. Dobbin and J. B. Reeside, Jr. *U. S. Geol. Survey Prof. Paper 158-B*. (Supt. Documents, Washington, D. C.), pp. 9-25, Pls. 4-5, Figs. 1-14.

"Die Entstehung des Erdöls, verwandter Kohlenwasserstoffe und gewisser Kohlenverkommen," by P. Krusch. *Petrol. Zeits.* (Berlin, November 6, 1929), pp. 1491-94.

"Betrachtungen über die Muttergesteine des Erdöls," by A. F. v. Stahl. *Petrol. Zeits.* (December 4, 1929), pp. 1626-27.

"Problem of Continental Geological Correlation," by Charles Keyes. *Pan-Amer. Geol.* (November, 1929), pp. 287-316, 3 figs.

GEOPHYSICS

The "Eötvös" Torsion Balance. (L. Oertling, Ltd., 65, Holborn Viaduct, London, E. C. 1). 90 pp., 21 figs. Price, £1 1 s.

Lehrbuch der Geophysik, by B. Gutenberg, E. A. Ansel, J. Bartels, H. Benndorf, A. Born, F. Linke, A. Sieberg, A. Wegener, and L. Weickmann. (Gebrüder Borntraeger, W. 35 Schöneberger Ufer 12 a. Berlin), xx and 999 pp., 412 illus. Price, bound, 80 RM.

JUGO-SLAVIA

"Der geologische Aufbau und das Erdölorkommen des Majevica-Gebirges," by Milan T. Luković. *Petrol. Zeits.* (Vienna, December 4, 1929), pp. 1619-26, Figs. 1-8. From the Serbian in "Rudarski i Topionički Vesnik," No. 2 (Beograd, 1929).

MONTANA

"The Kevin-Sunburst Oil Field and Other Possibilities of Oil and Gas in the Sweetgrass Arch, Montana," by A. J. Collier. *U. S. Geol. Survey Bull.* 812-B (Supt. Documents, Washington, D. C.), pp. 57-189, Pls. 11-18 (including 2 maps), Figs. 2-4. Price, \$0.30.

POLAND

"Quelques remarques sur la stratigraphie de l'avant-pays des Karpates Polonaises Orientales," by H. De Cizancourt. *Bull. du Service Geologique de Pologne* (Warsaw), Vol. V (1929), Nos. 1-2, pp. 318-42, Fig. 1, Pl. 8.

Geologie der polnischen Ölfelder, by Jan Nowak. (Ferdinand Enke, Stuttgart, 1929). 101 pp., 40 figs., 1 map. Price, 13 RM.

RUSSIA

"Searching for New Oilfields in Russia, by A. D. Archangelski. *Petroleum Times* (November 23, 1929), pp. 987-90, 1 map.

SOUTH AMERICA

Geologie en Geohydrologie van het Eiland Curaçao. By G. J. H. Molengraaf. (Martinus Nijhoff, Lange Voorhout 9, 'S-Gravenhage, Holland.)

WEST VIRGINIA

Detailed Report on Pocahontas County, by Paul H. Price. *West Virginia Geol. Survey* (Morgantown, June 17, 1929), 531 pp., 71 half-tone plates, 22 zinc etchings. Accompanied by separate case of topographic maps. Price, \$3.00; extra copies of topographic map, \$0.75; of geologic map, \$1.00.

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these applicants, please send it promptly to J. P. D. Hull, Business Manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each applicant.)

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NEW ORLEANS TECHNICAL PROGRAM, MARCH 20-22, 1930

The following preliminary list of authors and their papers promised for the New Orleans meeting of the American Association of Petroleum Geologists, March 20-22, 1930, gives an idea of the technical program which is being arranged by the committee under the chairmanship of F. H. Lahee, vice-president in charge of editorial work. Members planning to have papers on the New Orleans program are reminded that they must have a brief abstract or resumé, together with the title of the paper, in the hands of Dr. Lahee early in February if they wish a place on the New Orleans program. Manuscripts that are not on hand now (January 15) in completed form may not be preprinted.

PRELIMINARY LIST OF PAPERS

1. *Mississippi Embayment and Gulf Coast District*

- A. C. Trowbridge, "The Building of the Mississippi Delta"
 J. E. Lamar, "The Cretaceous and Tertiary Sediments of Missouri, Illinois, and Kentucky"
 C. L. Rankin, "Faulting in Southwestern Arkansas"
 J. S. Ross, "Deep Sand Developments in the Cotton Valley Field, Webster Parish, Louisiana"
 E. R. Ames, "Some Difficulties Encountered in the Development of Southern Louisiana Salt Domes"
 Ralph E. Grim, "Sedimentation in the Eastern Part of the Mississippi Embayment in Eocene Time"
 C. L. Moody, "Geological Map and Correlation Table of Mississippi, Louisiana, and Adjacent Parts of Texas and Arkansas"
 C. L. Moody, "Tertiary History of the Region of the Sabine Uplift"
 W. Armstrong Price, "Physiography of the Corpus Christi Area, Texas"
 A. G. Maddren, "The Refugio Field, Refugio County, Texas"
 R. A. Steinmayer, "Phases of Sedimentation in the Gulf Coastal Plain of Louisiana"
 W. C. Spooner and R. T. Hazzard, "The Comanche Series of Louisiana and Arkansas"

- John F. Weinzierl, "Blue Ridge Dome"
R. A. Liddle, "Geological and Geophysical Notes on the Van Structure, Van Zandt County, Texas"
F. E. Heath, J. A. Waters, and W. B. Ferguson, "The Clay Creek Field, Washington County, Texas"
L. F. McCollum, S. A. Burford, and C. J. Cunningham, "The Salt Flat Field, Caldwell County, Texas"
J. M. Wanenmacher and W. B. Gealy, "Surface and Subsurface Structure of the Tri-County Oil Field of Southwestern Indiana"
Charles Laurence Baker, "Contribution to the Cenozoic History of the Texas Plain"
Donald C. Barton, "Mapping of Formations in the Gulf Coastal Plain"
W. Armstrong Price, "The White Point and Saxet Fields"
Donald C. Barton, "The Producing Possibilities of the Gulf Coast Salt Domes"
M. A. Hanna, "The Post-Oligocene Subsurface Problem of Texas and Louisiana"
D. R. Semmes, "Oligocene and Miocene Formations of Southwestern Alabama"
D. R. Semmes, "Notes on Wells Penetrating the Cretaceous in Alabama and Georgia"

2. *Geophysics*

- Donald C. Barton, "Geophysical Prospecting for Oil"
Gail F. Moulton, "Magnetic Investigations North of the Illinois Oil Fields"
W. M. Barret, "Magnetometer Study of the Caddo-Shreveport Uplift"
R. A. Liddle, "Magnetometer Survey of the Little Fry Pan Area, Uvalde County, Texas"
H. R. Thornburgh, "Wave-Front Diagrams in Seismic Interpretation"
Donald C. Barton, "Review of Geophysical Prospecting for Petroleum"
R. Clare Coffin, "Geological and Geophysical Notes on Hobbs Oil Field, Lea County, New Mexico"

3. *Geological Aspects of the Crooked Hole Problem*

- P. C. Murphy and Sidney A. Judson, "Crooked Hole Problems in the Gulf Coast"
George A. Macready, "Orientation of Cores"

4. *Foreign Fields*

- B. B. Zavoico, "Geology of Russian Oil Fields"
Frederick G. Clapp, "A Reconnaissance in Northern Persia"
George Sheppard, "Geology of Southwest Ecuador"

5. *Geothermal Studies*

6. *Miscellaneous Subjects*

- Edson S. Bastin, "Data on Sulphate-Reducing Bacteria in Soils and Waters of Illinois Coal Fields"
- A. L. Ackers, R. DeChicchis, and R. H. Smith, "The Hendrick Pool, Winkler County, Texas"
- R. L. Clifton, "Permian Formations of Northwestern Oklahoma and Adjacent Areas"
- E. L. Jones and R. Conkling, "Igneous Rock in the Deep Shell Well in Pecos County, Texas"
- S. H. Knight, "Pre-Dakota Stratigraphy of the Rocky Mountain Front Range of Colorado and Wyoming"
- A. I. Levorsen, "The Pennsylvanian Overlap in the United States"
- P. D. Moore, "The Stratigraphy of the Turner Valley Field, Canada"
- W. T. Nightingale, "Geology of Vermillion Creek Gas Area in Southwest Wyoming and Northwest Colorado"
- Frank Rieber, "Some Results of Elastic-Wave Surveys in California and Elsewhere"
- Frank Rieber, "Factors Influencing the Selection of the Geophysical Method in Accordance with the Subsurface Problem to be Solved"
- R. J. Riggs and Homer Charles, "The Oklahoma City Pool"
- T. E. Weirich, "The Simpson of Central Oklahoma"

AT HOME AND ABROAD

W. F. CHISHOLM has resigned as supervisor of the Minerals Division of the Louisiana Department of Conservation located at Shreveport, after being supervisor since 1926. Robert Maestri, commissioner of conservation succeeding V. K. Irion, has appointed J. A. SHAW as the new supervisor. MR. CHISHOLM is now connected with the Halliburton Oil Well Cementing Company.

J. WHITNEY LEWIS, of Fort Worth, Texas, is examining oil properties in the Dominican Republic. He expects to return to Fort Worth in February.

R. B. RUTLEDGE is head of the geological department of the Shell Oil Company in Kansas. The geological and land departments of the company at El Dorado have been moved to Wichita, Kansas.

COLIN C. RAE, of the geological department of the Skelly Oil Company at Tulsa, Oklahoma, has been transferred to the production department with the title of geological engineer.

H. E. CRUM, district geologist for the Skelly at Amarillo, Texas, has been transferred to Tulsa to take charge of geological work in Oklahoma.

WILL BUTTRAM is associated with his brother FRANK BUTTRAM in California operations.

L. E. MITCHELL, formerly of the University of Nebraska, is employed in the geological department of the Skelly Oil Company.

EUGENE HOLMAN, of the Standard Oil Company of New Jersey, New York City, spent the early winter in South America.

W. DANA MILLER, representative of the Esperanza Oil Corporation, Venezuela, has been in New York City on business. The offices of the corporation are at 65 Broadway, New York.

The West Texas Geological Society has selected the following officers for the coming year: R. E. RETTGER, Sun Oil Company, San Angelo, president; GEORGES VORBE, Texas Pacific Coal and Oil Company, Midland, vice-president; and R. L. CANNON, Cannon and Cannon, San Angelo, secretary-treasurer. W. E. WRATHER, of Dallas, addressed the West Texas Geological Society on December 7 with a discussion of his trip through Africa. His talk was accompanied with motion pictures.

KENNETH DALE OWEN has resigned as district geologist for the Southern Crude Oil Purchasing Company, San Antonio, to become associated with the Penn Oil Company of Dallas, Texas. Mr. Owen, who plans to remain in southwest Texas, may be addressed at 2922 Broadway, San Antonio.

J. E. EATON, of Los Angeles, California, has an article in the December issue of *Petroleum World and Oil Age*, entitled "Geologists Have Their Faults, But Really, They're Not Bad Fellows."

LEW SUVERKROP, petroleum engineer, Bakersfield, California, wrote on "Why Hard-Faced Rotary Bits Dig Faster" in the December issue of the *Oil Bulletin*.

T. K. KNOX, of the Texla Royalty Company, Dallas, Texas, has an article entitled "Back Pressure and Gasoline Plant Accomplish Economies" in the December number of *Oil Field Engineering*.

LON D. CARTWRIGHT, JR., district geologist, is in charge of West Texas offices of the Superior Oil Company of California, recently transferred from Midland to San Angelo, Texas.

W. C. SPOONER, consulting geologist of Shreveport, Louisiana, has recovered from his recent illness.

W. E. WRATHER delivered a course of lectures at Yale University in January on the "Economics of the Petroleum Industry."

THOMAS S. HARRISON, consulting geologist, has returned to Denver after an extended residence in California.

A. E. FATH visited Cuba on professional business last fall.

M. G. Cheney, of Coleman, Texas, is living temporarily in Fort Worth, but is maintaining his office in Coleman.

WALLACE E. PRATT, director of the Humble Oil and Refining Company, Houston, Texas, was re-elected a director of the American Petroleum Institute.

RAY P. WALTERS has returned to Ploesti, Roumania, as chief geologist for the Standard Oil Company of New Jersey.

E. T. HANCOCK has resigned as chief geologist in Roumania for the Standard Oil Company of New Jersey to return to the United States.

DONALD C. BARTON lectured on geophysics at the University of Illinois in November.

K. D. WHITE, of the Standard Oil Company of New Jersey, has returned to Argentina.

DILWORTH S. HAGER has moved from San Antonio to Dallas, Texas.

RALPH W. RICHARDS, of the Standard Oil Company of New Jersey, has returned to Venezuela.

JOHN S. IVY is chief geologist for the Louisiana Gas and Fuel Company (formerly Palmer Corporation) of Shreveport, Louisiana.

ROBERT M. WHITESIDE, after several years with the Sinclair Oil and Gas Company, is now in charge of the micropaleontological work of the Shell Petroleum Corporation at Oklahoma City.

J. K. MURPHY, formerly assistant to the chief geologist of the Independent Oil and Gas Company at Tulsa, is now chief geologist with the Homestake Oil Company at Tulsa.

J. F. KINKEL, who has been in charge of geological work in Kansas for the Independent Oil and Gas Company, has been transferred to California, where he is in charge of geological work, with offices in the Quinby Building, Los Angeles, California.

JOHN H. NELIMARK, formerly district geologist in the Shawnee district, has been transferred to the Tulsa office of the Independent Oil and Gas Company in charge of subsurface work.

ROBERT MCNEELY, who has been doing detail work in western Kansas, has been transferred to Wichita in charge of geological work in Kansas for the Independent Oil and Gas Company.

GAIL F. MOULTON has resigned as geologist in charge of petroleum studies for the Illinois State Geological Survey, Urbana, to take charge of a geological office at Meridian, Mississippi, for the Louisiana Gas and Fuel Company. His address is Box 311, Meridian.

The M. M. Valerius Company, petroleum and mining geologists of Tulsa, Oklahoma, have moved to the Philcade Building.

At the regular monthly meeting of the San Antonio section of the A.A.P.G., December 2, D. C. BARTON, of Houston, Texas, gave a talk on the general subject of geophysics.

C. MCC. LEMLEY, formerly geological engineer for The Baltimore and Ohio System, Morgantown, West Virginia, has been appointed state geologist of West Virginia, succeeding the late I. C. WHITE.

IRVINE E. STEWART has resigned as chief geologist for The Texas Company of California. Mr. Stewart will engage in consulting practice at Los Angeles.

Analytical Principles of the Production of Oil, Gas, and Water from Wells, written by STANLEY C. HEROLD, and published by Stanford University Press, has been selected by the American Institute of Graphic Arts for inclusion in the "Fifty Books of the Year" exhibit arranged by the Institute. This annual exhibit is made up of the fifty books published in America which the judges consider outstanding examples of the bookmakers' art. Mr. Herold's book is the first Stanford University Press publication to be included in the exhibit.

THOMAS W. BUZZO is with the Sun Oil Company at Taylor, Texas.

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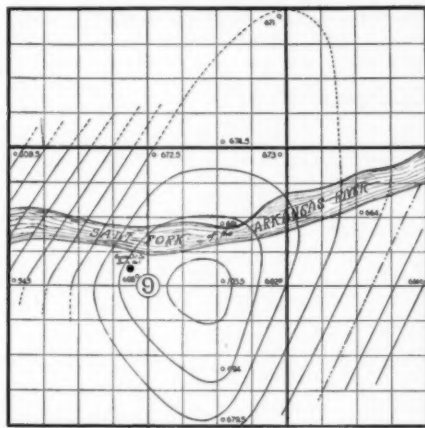
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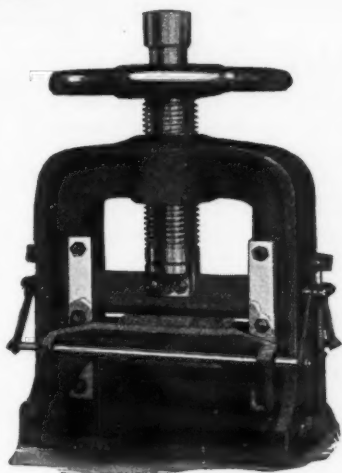
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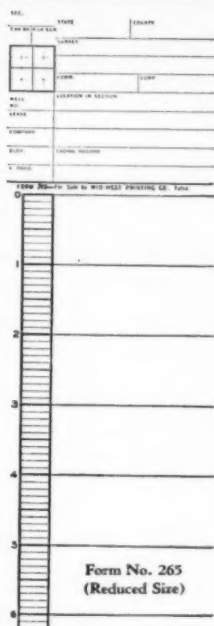
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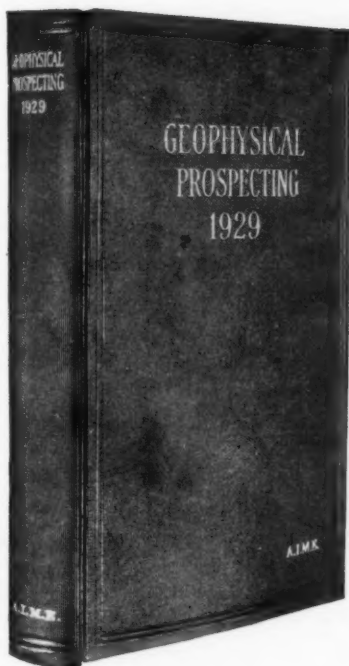
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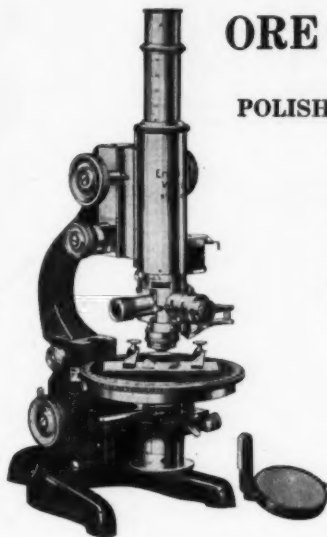
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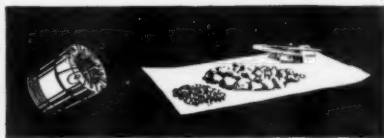
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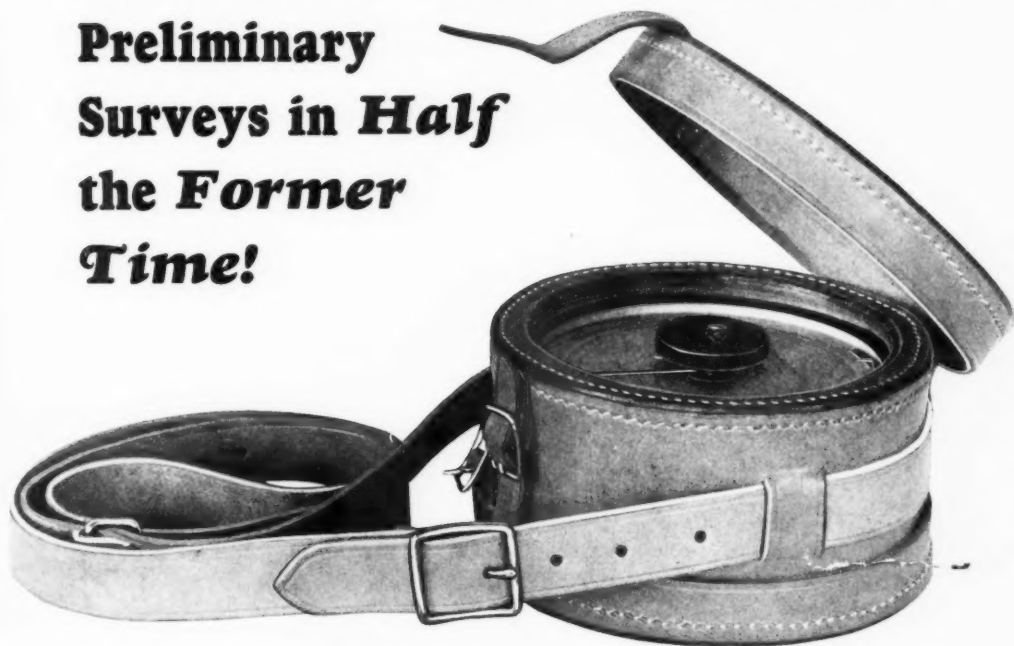
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